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Abstract

Water is an essential good for human life but there is controversy over whether it should be allocated using markets. In 1966, the irrigation community in Mula (Murcia, Spain) switched from a market institution, a 700 year old auction, to a system of fixed quotas with a ban on trading to allocate water from the town's river. We present a dynamic demand model in which farmers face liquidity constraints (LC) to explain why the new, non-market institution is more efficient. We show that ignoring the presence of LC biases the estimated (inverse) demand and demand elasticity downwards. We use the dynamic demand model and data from the auction period to estimate both farmers' demand for water and their financial constraints, thus obtaining unbiased estimates. In our model, markets achieve the first-best allocation only in the absence of LC. By contrast, quotas achieve the first-best allocation only if farmers are homogeneous in productivity. We compute welfare under both types of institutions using the estimated parameters. We find that the quota is more efficient than the market.

JEL Codes: D02, D53, L11, L13, G14, Q25.

Keywords: Institutions, Financial Markets, Demand, Dynamics, Market Efficiency, Water.

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1 Introduction

Water allocation is a central concern of policy discussions around the world. Seventy percent of fresh water usage worldwide is for irrigation. Water scarcity is extremely acute in places such as India, Latin America, and the U.S. (Vörösmarty *et al.*, 2010). Water markets (*e.g.* water auctions) are emerging as the preferred institution to allocate water in the developed world, particularly in dry regions of the U.S. and Australia (Grafton *et al.*, 2011). In the absence of *frictions*, a water auction is efficient because it allocates water according to bidders' valuations. When frictions are present, however, markets may not be efficient. Consider, for example, the friction that arises when bidders may not have enough cash to pay for water won in an auction (*i.e.* some bidders may be liquidity constrained). An auction allocates water to the highest bidders who are not liquidity constrained. A market failure occurs if some bidders, who are liquidity constrained, have higher valuations than the bidders who are not liquidity constrained. In such a case, other mechanisms may allocate water more efficiently than auctions.

When water markets are used, they are usually regulated, rather than free, markets. A common way to measure efficiency in water markets is to infer gains of trade from price differences. Such a measurement is difficult due to barriers across districts and different regulatory frameworks. Recovering demand in such cases requires strong assumptions about market participants (Libecap, 2011).

In this paper, we analyze how a market institution (an auction system) performs relative to a non-market institution (a quota system as described below) as a water allocation mechanism in the presence of frictions. The data in this paper comes from water auctions in a self-governed community of farmers in Mula, Spain. This allows us to exploit a unique scenario where a free market institution operated under a stable regulatory framework for over 700 years. From around 1244 until 1966, citizens of Mula used auctions to allocate water from their river among farmers. The farmers used this water for agricultural purposes. In 1966, the auction system was replaced by a quota system. Under the quota system, farmers who owned a plot of fertile land were entitled to a fixed amount of water—proportional to the size of their plot—for irrigation. Farmers paid only a small annual fee for maintenance costs.

Frictions arose in Mula when farmers did not have enough cash during the summer to purchase water from the auction. We provide evidence of these liquidity constraints (LC) in Section 2.3. Under the auction system, the price of water increased substantially during summer because (i) the agricultural products cultivated in the region (apricots, peaches, oranges, *etc.*) needed more water during this season of rapid fruit growth, thus increasing demand for water in the auction; and (ii) weather seasonalities in southern Spain generated less rainfall in summer than in winter. These conditions made summer the "critical" season.

In the lead article of the first volume of the *American Economic Review,* Coman (1911) pointed out this issue: "In southern Spain, where this system obtains and water is sold at auction, the water rates mount in a dry season to an all but prohibitive point." During the critical season, only "wealthy" farmers could afford to buy water. But "poor" farmers with the same production technology (*i.e.* the same agricultural products) would also benefit from buying water during the critical season. Indeed, we find that poor farmers bought less water during the critical season than wealthy farmers who had the same type of agricultural products and the same number of trees. A natural question arises: How did the institutional change from auctions to quotas affect welfare in the presence of LC?

In this paper, we empirically investigate how this institutional change—from auctions to quotas—affected efficiency as a measure of welfare. With output data (*i.e.* production data) before and after the institutional change, computing welfare would be straightforward. However, output data is not available either before or after the institutional change. We propose a structural econometric model that allows us to compute the output under auctions and quotas. The econometric model uses detailed input data (units of water purchased, rainfall amount, number of apricot trees, *etc.*) along with the apricot's production function (that transforms these inputs into apricots) to compute the counterfactual output before and after the institutional change. In the model, water for irrigation has diminishing returns and farmers are heterogeneous on two dimensions: their willingness to pay (productivity) and their ability to pay for the water (cash holdings). In the absence of LC, an auction system achieves the first-best (FB) allocation in a static setting. On the other hand, in the absence of heterogeneity in the farmers' productivity, a fixed quota system achieves the FB allocation, due to the decreasing marginal returns of water.[1] In our empirical setting, all farmers are heterogeneous in their productivity while some farmers are liquidity constrained. In this general case, the efficiency of auctions relative to quotas is ambiguous. It is then an empirical question to assess which institution is more efficient. To the best of our knowledge, no empirical study has investigated the efficiency of auctions relative to quotas in the presence of liquidity constrained bidders.

We start our empirical analysis by estimating the demand for water under the auction system. To estimate demand, we account for three features of the empirical setting. First, irrigation increases the moisture level of the land, thus reducing future demand for water. It creates an intertemporal substitution effect where water today is an imperfect substitute for water tomorrow because it evaporates over time. The resulting dynamics in the irrigation demand system are similar to those in the storable goods demand system. Soil's moisture level in the former plays an analogous role to inventory in the latter (*e.g.* Hendel and Nevo, 2006). Second, some farmers are liquidity constrained. Wealthy farmers strategically delay their purchases and buy water during the critical season, when agricultural products need water the most. Poor farmers, who may be liquidity constrained, buy water before the critical season in anticipation of price increases. Finally, weather seasonality increases water demand during the critical season, when fruit grows more rapidly. Seasonality shifts the whole demand system, conditional on intertemporal substitution and LC.

[1] If capital markets are perfect or if all farmers are sufficiently wealthy, then the auction system achieves the FB allocation in a static setting. If there is no heterogeneity (*i.e.* if all farmers have the exact same production function), then the quota system achieves the FB allocation. If there is no heterogeneity and all farmers are sufficiently wealthy, then both mechanisms (auctions and quotas) achieve the FB allocation. In a dynamic setting the characterization of the FB allocation is more complex and it includes the probability distribution of the evolution of the supply of water and future irrigtion.

To account for the intertemporal substitution effect, we condition water demand on the moisture level of the soil. The moisture level is not directly observable (similar to Hendel and Nevo, 2006, where the inventory is not directly observed). However, we observe rainfall and irrigation. We apply findings from the literature in agricultural engineering to construct a moisture variable for each farmer. The moisture variable measures the amount of water accumulated in each farmer's plot.

We show that ignoring the presence of LC biases the estimated (inverse) demand and demand elasticity downwards. To see this, consider the decrease in demand due to an increase in price during the critical season. When farmers are liquidity constrained, the decrease in demand has two components: (1) the decrease in demand due to the price being greater than the valuation of certain farmers; and (2) the decrease in demand due to some farmers being liquidity constrained, even when their valuation is above the prevailing price. If we do not account for the second component, we would attribute this decrease in demand to greater price sensitivity. Thus, one would incorrectly interpret LC as more elastic demand, biasing the estimated demand downwards.

To identify LC, we use the fact that wealthy farmers are never liquidity constrained, while poor farmers *may* be liquidity constrained in a given week. We focus on the set of farmers who only grow apricot trees and who thus share the same production function. Water, in our setting, is an intermediate good used to produce apricots. Thus, the demand for water is independent of the income (or wealth) of the farmer as long as the farmer has enough cash to pay for the water (*i.e.* no income effects).

In our econometric model the farmer's utility has three components. First, the apricot's production function that transforms water into apricots. This production function is obtained from the literature in agricultural engineering. Second, the cost of producing the apricots, measured as the amount spent on water plus an irrigation cost. Finally, an idiosyncratic productivity shock that is farmer specific. Conditional on the soil's moisture level, the type of agricultural product (*i.e.* apricot), and the number of trees, farmers' productivity is assumed to be homogeneous up to the idiosyncratic shock. This gives us the exclusion restriction to identify the other source of heterogeneity, LC.

As mentioned above, estimating demand using data for all farmers results in an underestimation of the price elasticity of demand. But wealthy farmers are never liquidity constrained. So we estimate demand using only data on wealthy farmers. For the estimation, we construct a conditional choice probability estimator (Hotz and Miller, 1993). We then use the estimated demand system and data on poor farmers to estimate the probability that poor farmers are liquidity constrained each week. We rely on the variation of two sources of financial heterogeneity, urban real estate value and revenue from previous years' harvests, in order to identify these parameters.

We use the estimated demand system to compare welfare under auctions, quotas, and the highest-valuation allocation. We consider the following allocation mechanisms: (1) Auctions, Ac, wherein water units are assigned to the farmer who bought them, as observed in the data; (2) Quotas with sequential assignment, $QX\%$, wherein every time we observe that a farmer bought a unit of water, the complete unit of water is assigned among the X% of farmers who went without irrigation the longest, proportional to their amount of land; and (3) the highest-valuation allocation, HV, wherein every time we observe that a farmer bought a unit of water, the complete unit of water is assigned to the farmer who values water the most.

We show that the following ranking holds in terms of efficiency: $HV > Q25\% > Ac$. The welfare under $Q25\%$ is greater than under Ac. Quotas increase efficiency when units are allocated according to $Q25\%$, which is a result of the concavity of the production function, the presence of LC, and the low heterogeneity in farmers' productivity (all farmers have the same production function: the apricot's production function). Under $Q25\%$ there are still gains to be made relative to the HV allocation, suggesting that there is some heterogeneity in productivity. In Mula, the quota allocation mechanism was close to $Q25\%$ because each farmer was assigned a certain amount of water, proportional to their plot's size, every three weeks (González Castaño and Llamas Ruiz (1991).[2]

In summary, we make three main contributions: (1) we combine a novel data set, including detailed financial and individual characteristic information, with a new econometric model to estimate demand in the presence of storability, LC, and seasonality; (2) we investigate the efficiency of auctions relative to quotas in the presence of liquidity constrained bidders by exploring a particular historical institutional change in southern Spain (Mula); (3) from an historical perspective, we conclude that the institutional change in Mula was welfare improving because the quota system more often allocated water units following farmers' valuations than did the auction system.

1.1 Related Literature

Scholars studying the efficiency of irrigation communities in Spain have proposed two competing hypotheses to explain the coexistence of auctions and quotas. On the one hand, Maass and Anderson (1978) claimed that, absent operational costs, auctions are more efficient than quotas. They argued that both systems nevertheless existed because the less efficient system (quotas) was simpler and easier to maintain. Hence, once operational costs are take into account, quotas were more efficient than auctions in places with less water scarcity. This hypothesis is supported by observations of auctions in places where water was extremely scarce (Musso y Fontes, 1847; Pérez Picazo and Lemeunier, 1985). On the other hand, Garrido (2011) and González Castaño and Llamas Ruiz (1991) argued that owners of water rights had political power and were concerned only with their revenues, regardless of the overall efficiency of the system.

The theoretical literature on auctions with liquidity constraints (LC) is recent (*e.g.* Che and Gale, 1998). Our model is closest to that of Che, Gale and Kim (2013). Che, Gale and Kim (2013) assume that agents can consume at most one unit of a good with linear

[2] In $Q50\%$, complete units of water are allocated among the 50% of farmers who have received less water in the past, in proportion to their amount of land. The welfare under $Q50\%$ is similar to the welfare under Ac. In $Q100\%$, complete units of water are allocated uniformly at random among all farmers, in proportion to amount of land. The welfare under $Q100\%$ is lower than under Ac. See Section 6 for details.

utility in their type. They conclude that markets are always more efficient than quotas, although some non-market mechanisms can outperform markets when resale is allowed. In our model we allow agents to consume multiple units with a concave utility function and we incorporate dynamics (intertemporal substitution). In our setting, there is no strict ranking between markets and quotas, but non-market mechanisms with resale can still outperform both markets and quotas.

Auctions with LC can be seen as a particular case of asymmetric auctions. If some bidders face LC, giving preferential treatment to those bidders could increase efficiency (Marion, 2007). Athey, Coey and Levin (2011) and Krasnokutskaya and Seim (2013) conclude that preferential auctions decrease efficiency if they reallocate from high-bid bidders to low-bid bidders. However, if LC bidders have higher valuations than unconstrained bidders, this reallocation would increase efficiency. Identifying valuations from LC is necessary in order to estimate efficiency gains in preferential auctions. Ignoring the presence of LC in preferential auctions could bias the estimated distribution of valuations downwards. Moreover, if firms face capacity constraints, as in Jofre-Bonet and Pesendorfer (2003), then small firms would be more efficient than large firms when the latter have high capacity contracted. Since small firms are also more likely to face liquidity constraints, the presence of capacity constraints would further increase the bias against small firms.[3]

Recent macroeconomic research points to the importance of financial constraints and the dynamics of wealth accumulation in the real economy (Moll, 2014). Imperfect capital markets are particularly important in developing countries (Banerjee and Moll, 2010). Rosenzweig and Wolpin (1993) estimate a structural model of agricultural investments in the presence of credit constraints. Udry (1994) studies how state-contingent loans are used in rural Nigeria to insure against some portion of output's variability. Laffont and Matoussi (1995) show how insufficient working capital affects contract arrangements in rural

[3]A normative implication is that the government/auctioneer increases efficiency by treating small firms' bids favorably. A positive implication is that treating bids of small firms as unconstrained bids would underestimate the productivity of small firms.

Tunisia. Jayachandran (2013) demonstrates that the presence of LC among land owners in Uganda renders upfront payment in cash more effective than promised future payments. Bubb, Kaur and Mullainathan (2016) study rural India, where, as in our case, water market LC reduces efficiency. We are not aware of any empirical paper analyzing the effect of LC in an auction setting. Pires and Salvo (2015) find that low income households buy smaller sized storable products (detergent, toilet paper, *etc.*) than do high income households, even though smaller sized products are more expensive per pound. They attribute this puzzling result to low income households' liquidity constraints.

We estimate a dynamic demand model with seasonality and storability. There is a vast empirical industrial organization (IO) literature on dynamic demand (*e.g.* Boizot *et al.*, 2001; Pesendorfer, 2002; Hendel and Nevo, 2006, 2011; Gowrisankaran and Rysman, 2012).[4] However, none of this work examines how LC affects demand. To the best of our knowledge, our paper is the first to propose and estimate a demand model with storability, seasonality, and LC. Timmins (2002) studies dynamic demand for water and is closest to our paper, although he estimates demand for urban consumption rather than demand for irrigation. Moreover, while Timmins (2002) uses parameters from the engineering literature to estimate the supply of water, we use parameters from the literature in agricultural engineering to determine both the demand structure and soil's moisture levels (see Appendix A.2).

2 Environment and Data

2.1 Environment

Southeastern Spain is the most arid region of Europe. The region is located to the east of a mountain chain, the Prebaetic System. Rivers flowing down the Prebaetic System provide the region with irrigation water. Most years are dryer than the average. There are only a

[4]See Aguirregabiria and Nevo (2013) for a recent survey.

few days of torrential rain but they are of high intensity.[5]

Weekly prices of water in the auction are volatile. These prices depend on the season of the year and the amount of rainfall. Since rainfall is difficult to predict, it is also difficult to predict the need for cash to buy water in the auction. Water demand is seasonal, peaking during the weeks when fruit grows most rapidly before the harvest. Farmers sell their output after the harvest, once per year. Only then do farmers collect cash (revenue) from growing their agricultural products. Hence, the weeks when farmers need cash the most to pay for water in the auctions (the weeks before the harvest) are the weeks furthest away from the last harvest (the last time they collected revenue). As a consequence, poor farmers who do not have other sources of revenue may be liquidity constrained.

Given that demand is seasonal, farmers take into account the joint dynamics of water demand and price when making auction's purchasing decisions. Water today is an imperfect substitute for water tomorrow. Future water prices are difficult to predict. Farmers consider current prices of water and form expectations about future prices of water. A farmer who expects to be liquidity constrained during the critical season—when the demand is highest—may decide to buy water several weeks before the critical season, when the price of water is lower. We allow farmers to save so that after a rainy year with low water prices, they are less likely to be liquidity constrained.

Farmers are "hand-to-mouth" consumers (González Castaño and Llamas Ruiz, 1991) in that they only have enough money for their basic necessities. A farmer who expects to be liquidity constrained in the future will attempt to borrow money. However, poor farmers in Mula did not have access to credit markets.[6] Even if a credit market is in place, lenders may not grant loans. In the presence of limited liability (*i.e.* the farmer is poor) and non-enforceable contracts (*i.e.* poor institutions), endogenous borrowing constraints emerge (see

[5] For example, 681 millimeters (mm) of water fell in Mula on one day, 10^{th} October 1943, while the yearly average in Mula is 326 mm. Summers are dry; rain falls mostly during fall and spring. The region's insolation is the highest in Europe.

[6] Personal interviews with surviving farmers confirm that some farmers were liquidity constrained —they did not have enough cash to buy their desired amount of water— yet they did not borrow money from others.

Albuquerque and Hopenhayn, 2004, for a model of endogenous liquidity constraints). Hence, even if a credit market exists, non-enforceable contracts would prevent farmers from having cash when they need it most.[7]

2.2 Institutions

Auctions. Since the 13^{th} century Spanish farmers used a sequential outcry ascending price (or English) auction to allocate water. The basic structure of the sequential English auction remained unchanged from the 13^{th} century until 1966, when the last auction was run. The auctioneer sold each of the units sequentially and independently of each other. The auctioneer tracked the buyer's name and price for each unit of water sold. Farmers had to pay in cash on the day of the auction.[8]

Water was sold by *cuarta* (quarter), a unit that denoted the right to use water flowing through the main channel during three hours at a specific date and time. Property rights to water and land were independent: some individuals, not necessarily farmers, were Waterlords. Waterlords owned the right to use the water flowing through the channel. The other farmers who participated in the auctions owned only land.

Water was stored at the main dam (*Embalse de La Cierva*). A system of channels delivered water to the farmer's plot. Water flowed from the dam through the channels at approximately 40 liters per second. Each unit of water sold at auction (*i.e.* the right to use water from the canal for three hours) carried approximately 432,000 liters of water. During our sample period, auctions were held once a week, every Friday.

During each session, forty units were auctioned: four units for irrigation during the day

[7] In contrast to German credit cooperatives (Guinnane, 2001), the farmers in southeastern Spain were not able to create an efficient credit market. Spanish farmers were poorer than German farmers and, more importantly, the weather shocks were aggregate (not idiosyncratic) and greater in magnitude. Hence, in order to reduce the risk, Spanish farmers should resort to external financing. However, external financing have problems such as monitoring costs and information acquisition that credit cooperatives do not have.

[8] Allowing the farmer to pay after the critical season would help mitigate the problems created by the LC and would increase the revenue obtained in the auction. The fact that the payment should be made in cash, as explicitly written in their bylaws, suggests that the water owners were concerned about repayment after the critical season (*i.e.* non enforceable contracts).

(from 7:00 AM to 7:00 PM) and four units for irrigation during the night (from 7:00 PM to 7:00 AM) on each weekday (Monday to Friday). The auctioneer first sold twenty units corresponding to the night-time and then twenty units corresponding to the day-time. Within the day and night groups, units were sold starting with Monday's four units and finishing with Friday's units. Our sample consists of all water auctions in Mula from January 1955 until July 1966, when the last auction was run.

Quotas. On August 1, 1966 the water allocation system switched from an auction to a quota system. Since 1966, the *Sindicato de Regantes* has allocated water to each farmer through a fixed quota. Under this system, water ownership was tied to land ownership. Each plot of land was assigned some amount of irrigation time during each three weeks round (*tanda*). The amount of time allocated to each farmer was proportional to the size of their plot. Every December, a lottery assigned a farmer's order of irrigation within each round. The order did not change during the entire year. At the end of the year, farmers paid a fee to the *Sindicato* proportional to the size of their plot. Farmers paid after the critical season, and were not liquidity constrained.[9] The fee covered the year's operational costs: guard salaries, channel cleaning, dam maintenance, *etc.*

2.3 Data

We examine a unique panel data set where each period represents one week and each individual represents one farmer. Thus, the unit of observation is a farmer-week. The data was collected from four sources. The first source is the weekly auction. For the period from January 1955 until the last auction, in July 1966, we observe the price paid, the number of units bought, the date of the purchase, and the date of the irrigation. This data was obtained

[9]The farmer was the owner of the water under the quota system, so the price that the farmer paid was the average cost of operation, which was smaller that the average price paid per unit of water under the auction system. A full accounting of costs will include the amortization of the value of water rights.

from the municipal archive of Mula.[10] The second source is rainfall measurements.[11] The third source is a cross sectional agricultural census from 1955. The census data contains information regarding the farmer's plots, including type of agricultural product, number of trees, production, and sale's price.[12] The final source is urban real estate tax records from 1955. We use this information to identify liquidity constraints (LC).

Table 1 shows the summary statistics of selected variables used in the empirical analysis. Detailed information about the data can be found in Appendix A.1.

Table 1: Summary Statistics of Selected Variables.

Variable	Mean	St. Dev.	Min	Med	Max	No. obs.
Weekly rain (*mm*)	8.29	37.08	0	0	423.00	602
Water price (*pesetas*)[a]	326.157	328.45	0.005	217.9	2,007	602
Real estate tax (*pesetas*)	482.10	1,053.6	0	48	8,715	496
Area (*ha*)	2.52	5.89	0.024	1.22	100.1	496
Number of trees[b]	311.3	726.72	3	150	12,360	496
Units bought	0.0295	0.3020	0	0	4	145,684

Notes: This is the sample of all farmers. We found 496 census cards in the archive. We were able to fully match 242 individuals to the auction data. The agricultural census include farmers who have only *secano,* or dry, lands and thus, are not in our sample. The sample after the matching process consists of 602 weeks and 242 individuals for a total of 145,684 observations.
[a] Water price is the weekly average price in the auction.
[b] Number of trees includes vines.
Source: Own elaboration.

Auction Data. Auction data (602 weeks) can be divided into three categories based on bidding behavior and water availability: (i) Normal periods (300), where for each transaction the name of the winner, price paid, date and time of the irrigation for each auction were registered; (ii) No-supply periods (295), where due to water shortage in the river or damage to the dam or channel—usually because of intense rain—no auction was carried out, and finally; (iii) No-demand periods (7), where not all 40 units were sold due to lack of demand

[10]From the section *Heredamiento de Aguas*, boxes No.: HA 167, HA 168, HA 169 and HA 170.
[11]We obtain the rainfall information from the *Agencia Estatal de Metereología*, AEMET (the Spanish National Meteorological Agency).
[12]Census data is obtained from the section *Heredamiento de Aguas* in the historical archive of Mula, box No. 1,210.

(the price dropped to zero due to recent rain). In the main estimation we use data for the period 1955-66.

Rainfall Data. In regions with Mediterranean climate, rainfall occurs mainly during spring and fall. Peak water requirements for products cultivated in the region are reached in spring and summer, between April and August. The coefficient of variation of rainfall is 450% ($^{37.08}/_{8.29} \times 100$), indicating that rainfall varies substantially.

Agricultural Census Data. The Spanish government conducted an agricultural census in 1955 to enumerate all cultivated soil, crops' production, and agricultural assets available in the country. The census recorded the following individual characteristics about farmers' land: type of land and location, area, number of trees, production, and the price at which this production was sold in the census year. We match the name of the farmer on each census card with the name of the winner of each auction.

Urban Real Estate Tax Data. In order to credibly identify the source of financial constraints, we require a variable related to farmers' wealth but unrelated to their demand for water. We use urban real estate taxes. (Note that farmers grow their agricultural products in rural areas, so urban real estate constitutes non-agricultural wealth.) The idea is that farmers with expensive urban real estate are wealthier than farmers who own inexpensive urban real estate. Thus, farmers with expensive urban real estate are unlikely to be liquidity constrained. On the other hand, the value of urban real estate owned should not affect the farmer's production function (*i.e.* the farmer's willingness to pay), conditional on the type of agricultural product, the size of the plot, and the number of trees. Hence, after accounting for these variables the value of the urban real estate should not be correlated with a farmer's demand for water, which is determined by the production function of the agricultural product (the apricot's production function in our case). We later use this exclusion restriction to identify liquidity constrained farmers.

2.4 Preliminary Analysis

In this subsection, we provide descriptive patterns from the data. Four main fruit tress grow in the region: orange, lemon, peach, and apricot. Oranges are harvested in winter, when water prices are low; thus farmers are unlikely to face liquidity constraints (LC). The other three types of fruit are harvested in the summer. We focus on apricots because they are the most common of these summer crops.

In Table 2 we restrict attention to farmers who grow only apricot trees. The table displays OLS regressions. We regress the number of units bought by each farmer in a given week on several covariates. The variable “High urban real estate” is a variable that equals 1 if the value of the urban real estate owned by the farmer is greater than the sample median and 0 otherwise. The idea behind this dummy variable is that farmers who are wealthy enough are never liquidity constrained. They do not have to pay rent for their houses and they can collect rent from their urban real estate to obtain cash during the critical season, financing their purchases. Consider two farmers who are growing apricots, who have the same number of trees, and who are not liquidity constrained. Water demand is determined by the tree’s water need according to the apricot’s production function. These two farmers should have the same demand for water up to an idiosyncratic shock. Therefore, there is no relationship between the demand for water and the monetary value of urban real estate.[13]

Wealthy farmers own larger plots. Since farmers can only buy whole units of water, there may be economies of scale in water purchases which only wealthy farmers (who own larger plots) can take advantage of. Table 2 displays estimates normalized for the number of trees on each farmer’s plot. Columns 1 and 2 shows that poor farmers buy less water overall. Wealthy farmers demand more water per tree during the critical season than poor farmers who have the same agricultural products (here, apricots). In columns 3 and 4 we include an interaction between “High urban real estate” and “Critical season.” The variable “Critical

[13] We obtain similar results using the 40^{th} or the 60^{th} percentiles of the distribution of urban real estate. Results are available upon request.

Table 2: Demand for Water per tree and Urban Real Estate.

# units bought per tree	(1)	(2)	(3)	(4)	(5)	(6)
High urban real estate	0.0131***	0.0073	0.0066	0.0017	0.0058	-0.0002
	(0.0042)	(0.0044)	(0.0044)	(0.0047)	(00.49)	(0.0051)
(High urban real estate)			0.0374***	0.0315***	0.0383***	0.0326***
x (Critical season)			(0.0091)	(0.0094)	(0.0093)	(0.0094)
(High urban real estate)					0.0039	0.0104
x (Weeks 1-10)					(0.0092)	(0.0101)
Covariates	No	Yes	No	Yes	No	Yes
Number of observations	14,448	14,448	14,448	14,448	14,448	14,448

Notes: All regressions are OLS specifications. The sample is restricted to farmers who only grow apricots. The dependent variable is the number of units bought by each individual farmer during a given week per tree. “High urban real estate” is a dummy variable that equals 1 if the value of urban real estate of the farmer is above the median and 0 otherwise. “Critical season” is a dummy variable that equals 1 if the observation belongs to a week during the critical season and 0 otherwise. “Weeks 1-10” is a dummy that equals 1 if the observation belongs to one of the first ten weeks of the year and 0 otherwise. “Covariates” are the price paid by farmers in the auction, the amount of rainfall during the week of the irrigation, and the farmer’s soil’s moisture level. Standard errors in parentheses. * p<0.10; ** p<0.05; *** p<0.01.

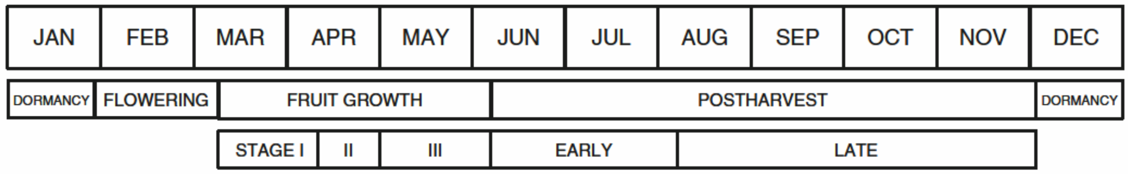
season" is a dummy variable that equals 1 if the observation belongs to a week during the critical season and 0 otherwise (see Figure 1 and its discussion on p. 16 for the definition the critical season). During the critical season, the auction price of water increases substantially because farmers need water the most. In the case of apricots, the critical season coincides with the beginning of summer, when prices are highest. The interaction term is positive and statistically different from zero. This means that wealthy farmers buy substantially more water than poor farmers during the critical season. Poor farmers who are liquidity constrained are not able to buy water during the weeks in which they need it the most. Columns 3 and 4 show that the effect of LC on the demand for water is concentrated on the critical season.

The bottom panel in Figure 2 may indicate that poor farmers also buy less water per tree than wealthy farmers during the first 10 weeks of the year. As a robustness check, in columns 5 and 6 in Table 2 we also include the interaction between "High urban real estate" and an indicator for purchases during the first 10 weeks of the year. The coefficient of this interaction is not statistically different from zero. Although not reported in Table 2, poor farmers who are liquidity constrained and are not able to buy water during the critical season, buy more water outside the critical season to "reconstruct" the moisture level in their plots (*i.e.* to prevent the trees from withering).

Water Demand and Apricot Trees. Figure 1 displays the seasonal stages of the typical apricot tree that is cultivated in Mula, the *búlida* apricot. These trees need the most water during the late fruit growth (stages II and III) and the early post harvest (EPH). This defines the "critical" irrigation season for apricot trees (see Torrecillas *et al.* 2000 for details). Stage III corresponds to the period when the tree "transforms" water into fruit at the highest rate. The EPH period is important because of the hydric stress the tree suffers during the harvest (see Pérez-Pastor *et al.* 2009 for further details).

The top panel in Figure 2 shows the effect of weather seasonality on the price of water in

Figure 1: Seasonal Stages for “Búlida” Apricot trees.



Notes: *Source*: Pérez-Pastor *et al.* (2009).

the auction. The figure displays the average weekly prices of water and the average weekly rainfall in Mula. The shaded area corresponds to the critical season as defined above. The price of water increases substantially during the critical season because (1) apricots, along with other products cultivated in the region, require more irrigation during this season, increasing the demand for water in the auction; and (2) weather seasonalities in southern Spain generate less rainfall during these months (top panel in Figure 2).

The bottom panel in Figure 2 shows the purchasing patterns of wealthy and poor apricot’s farmers. The figure displays the average liters per tree that each farmer purchased in the auction. Wealthy farmers—who are not liquidity constrained—demand water as predicted by Figure 1. Wealthy farmers strategically delay their purchases and buy water during the critical season, when the apricot trees most need water. On the other hand, poor farmers—who may be liquidity constrained—display a bimodal purchasing pattern for water. The first peak occurs before the critical season, when water prices are relatively low (see top panel). Poor farmers buy water before the critical season because they anticipate that they may not be able to afford water during the critical season due to increased auction’s prices. A fraction of this water will evaporate, but the rest remains as soil’s moisture.

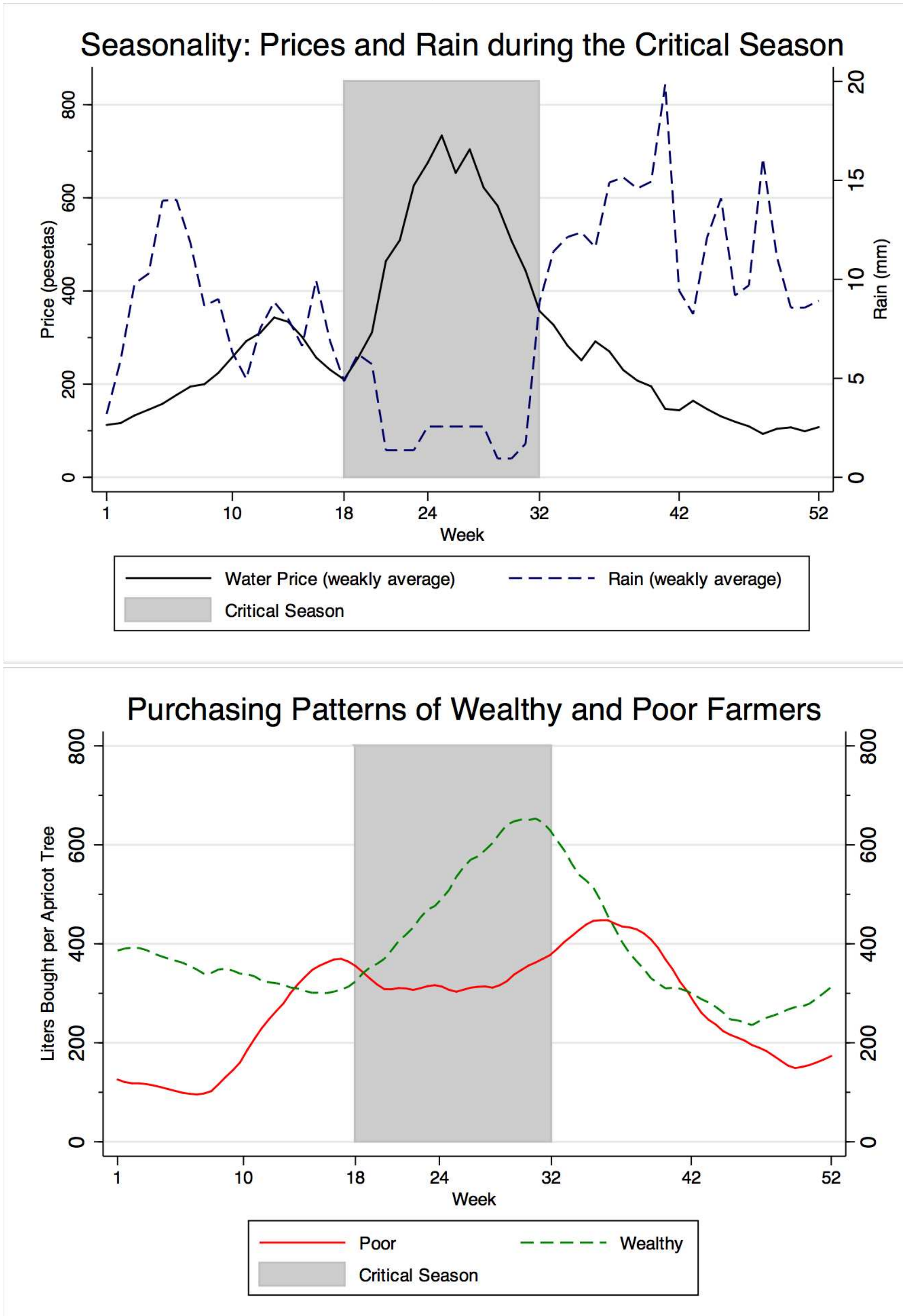
The second peak occurs after the critical season, when water prices are again relatively low. After the critical season, poor farmers’ plot have a low moisture level if they were unable to buy sufficient water during the critical season. Thus, poor farmers buy water after the critical season to prevent their trees from withering. This purchasing pattern for the poor farmers (high purchases before and after the critical season, and low purchases during the critical season) can be explained with a model that includes seasonality, storability, and liquidity constrains. That is what we do in Section 3.

3 The Econometric Model

In this section, we present the econometric model that allows us to compute welfare under auctions and under quotas. Computing welfare would be straightforward with output data (*i.e.* production data) before and after the institutional change. But this output data is not available. So we use detailed input data (units of water purchased, amount of rainfall , number of apricot trees, *etc.*) along with the apricot's production function (which transforms these inputs into apricots) to compute the output before and after the institutional change. We proceed in three steps. First, we present the econometric model. The econometric model uses the apricot's production function obtained from the literature in agricultural engineering and incorporates three features of our setting: storability, liquidity constraints (LC), and seasonality. Second, we estimate the model using the input data. Finally, we use the estimated model to compute the output under auctions and quotas. This allows us to perform a counterfactual analysis of welfare (*i.e.* production of apricot) before and after the institutional change.

Farmers used a sequential outcry ascending price (or English) auction to allocate water. Every week during each session, 40 units were auctioned: four units for irrigation during the day and four units for irrigation during the night on each weekday (Monday to Friday). In this paper we do not model the auction game and, thus, we abstract from the within-week variation in prices (see Donna and Espin-Sanchez 2015 for such a model). Instead we translate the auction mechanism into a simpler demand system, whereby individual farmers take prices as exogenous. This allows us to focus on the dynamic behavior of farmers across weeks. In this paper we focus on the demand system of the 24 farmers who only grow apricot trees. Note, however, that there are more than 500 farmers in the data set who can participate in the auction mechanism. Hence, we assume that the distribution of the highest

Figure 2: Seasonality and Purchasing Patterns of Wealthy and Poor Farmers.



Notes: The top panel displays: (1) the average weekly prices of water paid in the auction (left vertical axis), (2) the average weekly rain in Mula (right vertical axis), and (3) the critical season for apricots trees as defined in Figure 1 (shaded area). The bottom panel displays the average liters bought per farmer and per tree disaggregated by wealthy and poor farmers. A farmer is defined as wealthy if the value of urban real estate of the farmer is above the median. A farmer is defined as poor if the value of urban real estate of the farmer is below the median. The shaded area in the bottom panel displays the critical season (identical as in the top panel).

valuation among the other 500 farmers is exogenous to the valuation of a given farmer, conditional on the week of the year, on the price, and on the rain in the previous week. This is a credible assumption in our setting because it is unlikely that any individual apricot's farmer could affect the equilibrium price in the auction mechanism.[14]

We now describe the econometric model. The economy consists of N rational and forward-looking farmers, indexed by i, and one auctioneer. Water increases the farmer's soil's moisture level. So, from the point of view of the farmer, there are two goods in the economy: moisture, M, measured in liters per square meter (l/m^2) and money, μ, measured in *pesetas*. Time is denoted by t, the horizon is infinite, and the discount between periods (weeks) is $\beta \in (0,1)$. Demand is seasonal, hence some of the functions depend on the season. We denote the season by $w_t \in \{1,2,...,52\}$, representing each of the 52 weeks of any given year. In each period, the supply of water in the economy is exogenous.

Farmers only get utility for water consumed during the critical season. Water is an intermediate good. Hence, utility refers to the farmer's profit and is measured in *pesetas*, not in *utils*. Water bought in any period can be carried forward into the next period, but it "evaporates" as indicated by the evolution of the soil's moisture in equation 2 (*i.e.* water "depreciates" at some rate $\delta \in (0,1)$).

Farmers' preferences are represented by:

$$u\left(j_{it}, M_{it}, w_t, \mu_{it}, \varepsilon_{ijt}; \gamma, \sigma_\varepsilon, \chi\right) = h\left(j_{it}, M_{it}, w_t; \gamma\right) + \varepsilon_{ijt} - p_t j_{it} - \zeta_j + \mu_{it}, \tag{1}$$

where $h(\cdot)$, is the apricot's production function (common to all farmers) that is strictly increasing and concave in the moisture level of the farmer, M_{it};[15] ε_{ijt} is an additive productivity shock to farmer i in period t given that the farmer bought j_t units of water; p_t is a scalar that represents the price of water in the auction in period t (common to all farmers);

[14] In Appendix B.3 we present an econometric model that accounts for the within-week variation in prices. In the structural estimation we abstract from it because there is little variation in average prices (among several units) within a week across farmers (see Donna and Espin-Sanchez 2015 for details).

[15] For the estimation we use equation 6 (discussed below) obtained from the literature in agricultural engineering. See Appendix A.2 for details.

$j_{it} \in \{0, 1, ..., J\}$, is the number of units that farmer i buys in period t; μ_{it} is the amount of cash that farmer i has in period t; and $(\gamma, \sigma_\varepsilon, \chi)$ is a vector of parameters (to be estimated) that we describe below. Finally, ζ_j represents the cost that the farmer incurs when irrigating (this disutility could result, for example, if the farmer hires a laborer to help with irrigation). We restrict attention to the case where farmers do not incur irrigation costs if they do not irrigate ($\zeta_0 = 0$) and irrigation costs are constant across units ($\zeta_j = \zeta$ if $j > 0$).

Motivated by the historical context of Mula, we assume that farmers are "hand-to-mouth" consumers, *i.e.*, we require that $(\mu_{it} - p_t j_{it}) \geq 0, \forall j_{it} > 0$ (limited liability). Wealthy farmers obtain cash flow from their non-agricultural wealth, so they always have enough cash and the limited liability constraint is never binding. However, the constraint could be binding for poor farmers. Farmers are rational and forward-looking. They anticipate that the constraint may be binding in the future (*e.g.* critical season) and, thus, they buy water before the critical season, when prices are low.

Farmers in the economy differ from each other in two ways. First, they differ in their productivity shock, ε_{ijt}. Second, they differ in their wealth levels, μ_{it}. We describe the evolution of the wealth level below. Both, ε_{it} and μ_{it}, are private information.

State Variables

There are six state variables in the model:

- M_{it} (deterministic, measured in l/m^2): is the moisture level of the plot. It represents the amount of water accumulated in the farmer's plot.

- w_t (deterministic): is the weekly seasonal effect. Its support is $\{1, 2, ..., 52\}$.

- p_t (random, measured in *pesetas*): is the price for each unit of water during week t.

- r_t (random, measured in l/m^2): is the amount of rain that fell on the town during period t.

- $\epsilon_{it} \equiv (\epsilon_{i0t}, ..., \epsilon_{iJt})$ (random): is a choice specific component of the utility function.

- μ_{it}: represents the amount of cash that the individual i has at period t.

Evolution of the State Variables

Moisture. Trees on a farmer's plot die if the soil's moisture level falls below the permanent wilting point, PW, which is a scalar obtained from the literature in agricultural engineering. So each farmer i must satisfy the constraint $M_{it} \geq PW \ \forall t$. The law of motion for the moisture, M_{it}, is given by:[16]

$$M_{it} = min \left\{ M_{i,t-1} + r_t + \frac{j_{it} \cdot 432,000}{area_i} - ET\left(M_{it}, w_t\right), FC \right\}, \tag{2}$$

where r_t is the amount of rainfall (measured in mm) in Mula during period t; j_{it} is the number of units purchased by farmer i in period t; $432,000$ is the number of liters in each unit of water; $area_i$ is the farmer's plot area (measured in square meters); $ET\left(M_{it}, w_t\right)$ is the adjusted evapotranspiration in period t; and FC is the full capacity of the farmer's plot. Moisture and seasonality are the main determinants of water demand. The moisture level increases with rain and irrigation, and decreases over time as the accumulated water "evaporates" (evapotranspiration). Although the moisture level is not observable, both rain and irrigation are observable. We use equation 2 to compute the moisture level. Note that 2 accounts implicitly for decreasing marginal returns of water in two ways. First, because there is a maximum capacity in the farmer's plot (FC), farmers "waste" water if the moisture level increases above FC. Second, evapotranspiration (*i.e.* "depreciation" of the water in the farmer's plot) is greater for greater levels of moisture. Thus farmers with high levels of moisture in their plots "waste" more water *via* greater evapotranspiration.

Weekly Seasonal Effect. The evolution of the weekly season is deterministic:

[16] We follow the literature in agricultural engineering to compute the moisture. See appendix A.2 for details.

$$w_t = \begin{cases} w_{t-1} + 1 & \text{if} \quad w_{t-1} < 52 \\ 1 & \text{if} \quad w_{t-1} = 52 \end{cases}. \tag{3}$$

Farming is a seasonal activity. Each crop has different water requirements, depending on the season. The apricot water requirement is captured by the production function, $h(j_{it}, M_{it}, w_t)$. Since the market for water has a weekly frequency, we include a state variable with a different value for every week of the year.

Price of Water and Rainfall. The main determinant of both, the price of water in the auction and rainfall, is seasonality. Our unit of analysis is a week, so we work with average weekly prices and average weekly rainfall. Average weekly prices and average weekly rainfall vary substantially across weeks of the year (see Figure 2). However, for a given week, the variation of prices and rainfall across years is very low (see Donna and Espín-Sánchez, 2015, for details regarding the evolution of prices in the auctions).

We model the evolution of prices and rainfall to capture these empirical regularities. Our data covers a sample of 12 years. We assume that, holding fixed the week of the year, farmers jointly draw a price-rain pair, (p_t, r_t), among the 12 pairs (*i.e.* the 12 years of the same week) available in the data with equal probability.[17] Note that water for each week is auctioned on the Friday of the previous week. So when a farmer jointly draws a pair price-rain, the rain corresponds to the rain in the previous week of the irrigation. Thus, prices for the week of the irrigation are drawn conditional on the week of the year and the rainfall during the previous week. The rain during the previous week captures the dynamics of droughts (*i.e.* prices are systematically higher when there is no rain).

Productivity Shock. We assume that the productivity shocks, ε_{ijt}, are drawn *i.i.d.* (across individuals and over time) from a Gumbel distribution with CDF $F(\varepsilon_{it}; \sigma_\varepsilon) =$

[17]We obtain similar results by estimating the joint distribution of prices and rain nonparametrically conditional on the week of the year, and then drawing price-rain pairs from this distribution, conditional on the week of the year. Results are available upon request.

$e^{-e^{-\varepsilon_{it}/\sigma_\varepsilon}}$, where σ_ε is a parameter to be estimated. The variance of this distribution is given by $\sigma_\varepsilon^2\pi^2/6$. The higher the value of the parameter σ_ε, the more heterogeneous the distribution of productivity. We report the results using two specifications for the choice specific productivity shock:

Specification 1. The productivity shocks, ε_{ijt}, are drawn *i.i.d.* across units $j \in \{0, 1, \ldots, J\}$ (and across individuals and over time). Under this specification the productivity shock shifts the relative utility of every unit. So the productivity shock of buying one unit is independent of the one of buying two units, which is independent of the one of buying three units, *etc.*

Specification 2. The productivity shocks are drawn *i.i.d.* across the decisions of not buying, $j = 0$, and buying, $j > 0$ (and across individuals and over time). So every player receives one shock, but the shock is the same for every unit (see *e.g.* Kalouptsidi, 2015). Formally, let $\hat{j} \in \{0, 1\}$, where $\hat{j} = 0$ if $j = 0$ and $\hat{j} = 1$ if $j > 0$. Then the productivity shocks $\varepsilon_{i\hat{j}t}$ are drawn *i.i.d.* across $\hat{j} \in \{0, 1\}$ and the shock is the same for every unit, so $\varepsilon_{ijt} = \varepsilon_{i\hat{j}t}$ for $j = 0$ and $\varepsilon_{ijt} = j\varepsilon_{i\hat{j}t}$ for $j > 0$. Closed-form expressions of the conditional choice probabilities using this specification are in appendix B.

Cash Holdings. Farmer i's cash in period t, μ_{it}, evolves according to:

$$\mu_{it} = \mu_{i,t-1} - p_{t-1}j_{i,t-1} + \Phi_t\left(re_i; \phi\right) + \eta_{it} + \nu_{it}, \tag{4}$$

where $\Phi_t\left(re_i; \phi\right) = \phi_{i0} + \phi_1 re_i$ captures the (weekly) cash flow function derived from the real estate value, ϕre_i, minus individual i's average weekly consumption that is constant over time, ϕ_{i0}; η_{it} is the revenue the farmer obtains from selling the harvest (we present the revenue below in equation 9), and ν_{it} are idiosyncratic financial shock that are drawn *i.i.d.* (across individuals and over time) from a normal distribution. The revenue η_{it} is equal to 0 all weeks of the year, except the week after the harvest, when farmers sell their products and collect revenue. Note that ϕ_{i0} represents the average weekly consumption. So weekly consumption is not necessarily constant over time. This is our preferred interpretation.[18]

Value Function

The expected discounted utility of farmer i at $t = 0$ is then:

$$\begin{gathered}\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t \left[h\left(j_{it}, M_{it}, w_t; \gamma\right) + \varepsilon_{ijt} - p_t j_{it} - \zeta_j + \mu_{it}\right]\right] \\ \text{s.t. } M_{it} \geq PW \\ \text{s.t. } j_{it}p_t \leq \mu_{it}, \quad j_{it} > 0\end{gathered},$$

subject to the evolution of the state variables as described above. The expectation is taken over r_t, p_t, ε_{ijt}, and ν_{it}. Note that for wealthy farmers the constraint $j_{it}p_t \leq \mu_{it}$ is not binding. Then, the value function is:

$$\begin{gathered}V\left(M_{it}, w_t, p_t, r_t, \mu_{it}, \epsilon_{ijt}\right) \equiv \underset{j_{it}\in\{0,1,\ldots,J\}}{max} \{h\left(j_{it}, M_{it}, w_t; \gamma\right) + \varepsilon_{ijt} - p_t j_{it} - \zeta_j + \mu_{it} + \\ + \beta\mathbb{E}\left[V\left(M_{i,t+1}, \mu_{i,t+1}, w_{t+1}, p_{t+1}, r_{t+1}, \epsilon_{i,t+1}\right)|M_{it}, w_t, p_t, r_t, \mu_{it}, j_{it}\right]\} \\ \text{s.t. } M_{it} \geq PW \\ \text{s.t.} j_{it}p_t \leq \mu_{it}, \forall j_{it} > 0\end{gathered}, \quad (5)$$

subject to the evolution of the state variables as described above.

The Apricot's Production Function

The production function of the apricot tree is given by Torrecillas *et al.* (2000):

[18] A more flexible specification of equation 4 would allow the weekly consumption to depend on seasonal effects and cash holdings. However, given the data limitations (*e.g.* unobserved consumption decisions, unobserved cash flow derived from urban real estate, *etc.*) we prefer the current specification that is simple and transparent. (See appendix B for details.)

$$h\left(M_{t-1}, w_t; \gamma\right) = \left[\gamma_1 \cdot \left(M_{t-1} - PW\right) \cdot KS\left(M_t\right) \cdot Z_1\left(w_t\right) + \gamma_2 \cdot \left(M_{t-1} - PW\right) \cdot KS\left(M_t\right) \cdot Z_2\left(w_t\right)\right] \cdot area_i, \tag{6}$$

where $h\left(M_{t-1}, w_t; \gamma\right)$ is the harvest at period t; $\gamma \equiv (\gamma_1, \gamma_2)$ is a parameter vector that measures the transformation rate of the production function; $area_i$ is the size of the land (m^2) that farmer i owns, $KS\left(M_t\right)$ is the hydric stress coefficient (see appendix A.2), $Z_1\left(w_t\right)$ is a dummy variable that equals 1 during weeks 18-23 and 0 otherwise:

$$Z_1\left(w_t\right) = \begin{cases} 1 & \text{if} \quad 18 \leq week \leq 23 \\ 0 & \text{otherwise} \end{cases}, \tag{7}$$

and $Z_2\left(w_t\right)$ is a dummy variable that equals 1 during weeks 24-32 and 0 otherwise:

$$Z_2\left(w_t\right) = \begin{cases} 1 & \text{if} \quad 24 \leq week \leq 32 \\ 0 & \text{otherwise} \end{cases}. \tag{8}$$

The dummy variables $Z_1\left(w_t\right)$ and $Z_2\left(w_t\right)$ capture the seasonal stages of the typical apricot tree that is cultivated in Mula, as emphasized when we discussed Figure 1 (critical season). The characterization of γ is a direct application of results from the literature in agricultural engineering (Torrecillas *et al.*, 2000; Pérez-Pastor *et al.*, 2009). The parameter γ_1 measures the transformation rate of fruit during the fruit growth season. The parameter γ_2 measures the recovery of the tree during the early post-harvest stress season. Both parameters are measured in *pesetas* per *liter*.[19]

Given this payoff function, we compute the farmer's revenue in a given year:

[19] The production function measures production in *pesetas*. But the actual price at which the production is sold is determined in the output market. We do not have data on the price at which this production is sold. So we recover the revenue of the farmers up to this constant (the common price at which the production of all farmers is sold in apricot's market). This price only shifts the revenue function of all (wealthy and poor) farmers. So it does not affect our welfare analysis.

$$Revenue_t = \sum_{w_t=18}^{23} \gamma_1 \cdot (M_{t-1} - PW) \cdot KS\left(M_t\right) \cdot area_i + \sum_{w_t=24}^{32} \gamma_2 \cdot (M_{t-1} - PW) \cdot KS\left(M_t\right) \cdot area_i. \quad (9)$$

4 Estimation

We estimate the parameters of the model in two stages. In the first stage, we estimate the parameters that characterize demand, $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$, using data from wealthy farmers, excluding the data of poor farmers who may be liquidity constrained. In the second stage, we estimate the vector of financial parameters, χ, using the estimated parameters from the first stage, $\hat{\Theta}$. The exclusion restriction for the second stage is that poor farmers have the same production function as wealthy farmers, up to an idiosyncratic shock. Thus, we assume that there is no unobserved heterogeneity that affects the production function of wealthy and poor farmers differently.

4.1 First Stage: Demand Estimates

In the first stage, we construct a two-step conditional choice probability (CCP) estimator (Hotz and Miller, 1993) to estimate the parameters that characterize demand.

Step 1. In the first step we compute transition probability matrices for the following state variables: moisture, week, price, and rain. As described above, the productivity shocks ε_{ijt} are assumed to be *i.i.d.* Gumbel, so they can be integrated analytically under the two specifications described above. The transition probability of the cash holdings is estimated in the second stage. Moisture is a continuous variable and its evolution over time depends on both the farmers' decisions to buy water and rainfall. Therefore, certain values of moistness are never reached in the sample, even when their probability of occurrence is nonzero. To estimate demand, however, we need to integrate the value function for each possible combination of state variables in the state space. Thus, we first estimate the CCP using the values (of the state space) reached in the sample, using data only on wealthy farmers. Then we use the CCP estimator to predict the CCP on the values (of the state space) unreached in the sample.[20] (See appendix B for details.)[21]

Step 2. In the second step we build an estimator similar to the one by proposed by Hotz *et al.* (1994). We use the transition matrices to forward simulate the value function from equation 5. This gives us the predicted CCP by the model as a function of the parameters $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$. We estimate the parameter vector Θ using a GMM estimator based on moment conditions proposed by Hotz *et al.* (1994).

Identification. The exclusion restriction for the first stage is that wealthy farmers are not liquidity constrained. Under this exclusion restriction identification of Θ follows the standard arguments (*e.g.* see Hotz and Miller, 1993; Hotz *et al.,* 1994; Rust, 1996; Magnac and Thesmar, 2002; and Aguirregabiria, 2005). In our case the parameter vector γ is identified from the variation in purchasing patterns across seasons and the variation in moisture levels across farmers within the same season. The parameter ζ_j is constant across units and independent of the moisture level. It is identified from the variation in the level of prices and the farmer's decision of buying *vs.* not buying, holding constant the level of moisture. Finally, the parameter σ_ε represents the marginal utility of income in our model and is identified because our specification for the utility function of the farmer in equation (1) does

[20]We estimate the CCP both non-parametrically (using kernel methods to smooth both discrete and continuous variables) and parametrically (using a logistic distribution, *i.e.*, a multinomial logit regression).

[21]For the initial condition of the moisture we follow the standard approach in the industrial organization literature to deal with the unobserved initial condition of the inventory (see *e.g.* Hendel and Nevo 2006, p. 1647, where our unobserved initial moisture is analogous to Hendel and Nevo's unobserved initial inventory). The standard approach is to use the estimated distribution of cash holdings to generate the initial distribution. We do this by starting at an arbitrary initial level of moisture and using part of the data (the first 25 weeks of the first year) to generate the distribution of moisture implied by the model. For the arbitrary initial level of the moisture we use the moisture after the first harvest ($w_t = 24$) in 1955, the first year in our sample (which varies by farmer), assuming that all farmers started with a level of moisture of $1/2(TAW + PW)$, where TAW and PW are the Total Available Water and Permanent Welting Point as described in Appendix A.2. In practice, the initial condition of the moisture has no impact on its evolution after a couple of weeks because the evotranspiration rate is relatively large (*i.e.* large "depreciation"). We have experimented with different initial conditions and obtained almost identical results.

not include a parameter that multiplies the price of water. This parameter is typically called "α" in the industrial organization literature (see Berry, Levinsohn, and Pakes, 1995; Nevo, 2001; Hendel and Nevo, 2006) and measures the income sensitivity of a consumer. Since we are estimating a production function, the utility function in (1) is in pesetas ($), not in utils.

4.2 Second Stage: Financial Parameters

In the second stage, we estimate the financial parameters, χ, by maximum likelihood. In the data we only observe whether the poor farmer buys water or not, in addition to the number of units purchased. When a farmer does not buy water, we do not know whether it is because the farmer does not demand water and is not liquidity constrained, or whether the farmer is liquidity constrained. That is, for the poor farmers, the dependent variable is censored. So we compute the probability that a poor farmer i is liquidity constrained using the estimates from the first stage. The intuition behind this is that farmers are heterogeneous in two dimensions: their productivity and LC. Thus, a wealthy farmer and a poor farmer who have the same number of apricot trees only differ in the idiosyncratic productivity shock and their cash flow. Using the estimated parameters of the production function from the first stage (*i.e.* using the data of the wealthy farmers), we compute the probability that the poor farmer is liquidity constrained using the distribution of the idiosyncratic financial shock and treating the farmer's decision variable as a censored variable. This allows us to write the likelihood that a poor farmer is liquidity constrained (see appendix B.2 for details). The exclusion restriction for the second stage is that poor farmers have the same production function as the wealthy farmers (*i.e.* no unobserved heterogeneity).

5 Estimation Results

In this subsection we present the estimation results of the econometric model under different specifications.

Table 3: Structural Estimates

Estimates	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Transformation rate ($18 \leq week \leq 32$):								
– Linear term: $\hat{\gamma}_L$	0.1449 (0.0051)	0.1804 (0.0099)	0.2040 (0.0183)	0.10494 (0.0057)	0.1584 (0.0067)	0.1790 (0.0094)	0.2124 (0.0026)	0.0734 (0.0064)
– Quadratic term: $\hat{\gamma}_Q$	–	1.36e-04 (1.57e-05)	–	1.53e-04 (8.41e-06)	–	1.36e-04 (1.59e-05)	–	6.19e-05 (8.82e-06)
Irrigating cost: $\hat{\zeta}$	11.3193 (5.4146)	183.5007 (2.2251)	69.6141 (8.6176)	201.8714 (8.1738)	24.3755 (6.9848)	182.174 (13.2357)	78.8924 (3.1994)	34.3495 (6.76245)
Scale parameter of Gumbel distribution: $\hat{\sigma}_\varepsilon$	1.0252 (0.0116)	1.0321 (0.0601)	0.9923 (0.0786)	1.1987 (0.0612)	1.0100 (0.2568)	1.0854 (0.1286)	0.9361 (0.0393)	1.0144 (0.1048)
Area heterogeneity	No	No	Yes	Yes	No	No	Yes	Yes
Specification of the choice specific error term	1	1	1	1	2	2	2	2

Notes: Standard errors in parenthesis. See Subsection 6.1 for details about this table.

5.1 First Stage Results: Demand Estimates

Table 3 displays the estimation results from the first stage of the model from Section 3 (demand parameters $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$ from equation 5) using the estimation procedure from Subsection 4.1.

We present two sets of estimates using different specifications for the productivity shocks. In columns 1 to 4 we use specification 1 for the productivity shocks as described in Section 3. In columns 1 and 2 we perform the estimation with only one type of farmer who has the median number of trees from the sample ("Area heterogeneity: No"). This means that when we forward simulate the value function (as outlined in Subsection 4.1), $area_i$ from equation 6 is set to the median area for all individual farmers i. In column 1 we use the apricot's production function as outlined in equation 6 with $\hat{\gamma}_0 = \hat{\gamma}_1 \equiv \gamma_L$. The estimated transformation rate is $\hat{\gamma}_L = 0.15$. For robustness, in column 2 we add a quadratic term for moisture, γ_Q, to the specification in column 1 to incorporate potential increasing or decreasing marginal returns explicitly. However, the estimated coefficient for the quadratic term of the transformation rate is small in magnitude, $\hat{\gamma}_Q = 1.36e-04$. In columns 3 and 4 we repeat the estimation from the previous two columns using ten different discrete types of farmers, who differ only in their plot's area ("Area heterogeneity: Yes"). The area of each type corresponds to the number of trees owned by wealthy farmers in the data (there are 12 wealthy farmers in the data, but there are two pairs of farmers with the same area). Each discrete type has the same probability. This means that when we forward simulate the value function (as outlined in Subsection 4.1), the value of $area_i$ from equation 6 is drawn uniformly at random from a distribution with discrete support at the points $\{area_1, area_2, \ldots, area_{10}\}$. In Table 3 we report the mean $\Theta \equiv (\gamma, \sigma_\varepsilon, \zeta)$ across types. The estimated scale parameter of the Gumbel distribution (*i.e.* distribution of idiosyncratic productivity) is similar in magnitude across the specifications. The higher the parameter σ_ε, the higher the variance of the distribution of idiosyncratic productivity. When $\sigma_\varepsilon = 1$, the distribution of idiosyncratic productivity is a standard Gumbel. Finally note that, as expected, the estimated irrigation cost increases when we add the quadratic term for moisture and when use different farmers' types.

In columns 5 to 8 we repeat the estimation from columns 1 to 4 using specification 2 for the productivity shocks (see section 3). The overall estimates are similar to the first set of specifications.[22]

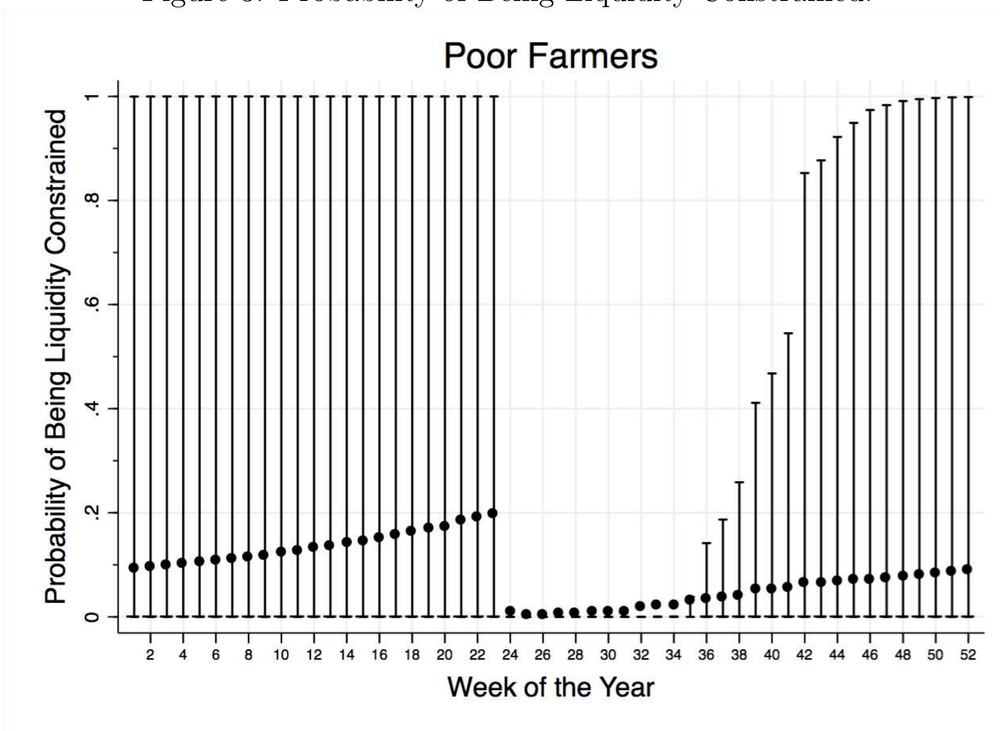
5.2 Second Stage Results: Financial Parameter Estimates

We estimate the financial parameters, χ, by maximum likelihood using a standard censored model. See Appendix B.2 for details.[23] We use these estimates to compute the probabilities that a given farmer is liquidity constrained in a given week. Figure 3 displays the empirical distribution (among the poor farmers) of the Probability of being Liquidity Constrained (PLC) given by: $PLC_i = \mathbb{P}\left(p_t j_{it} > \mu_{it}\right)$, where i index the poor farmers. Week 24 is the harvest (*i.e.* when the farmers collect their cash revenue). As expected, the PLC is close to zero after week 24 (*i.e.* after the harvest). This is because farmers have just collected cash revenue and trees do not require much water. However, for weeks 1-23 (*i.e.* before the harvest), there is substantial heterogeneity among poor farmers. Some of the poor farmers are liquidity constrained with probability one, while others are not liquidity constrained. The weeks before the harvest are the weeks furthest away from the last harvest and the weeks when the farmers need water the most. The mean PLC for weeks 1-23 lies between 9% and 20% (Figure 3).

[22] In a previous draft of this paper, we also obtained similar results using an specification that allows for different transformation rates for pre-season ($18 \leq week \leq 23$) and on-season ($24 \leq week \leq 32$).

[23] Table A1 in the in the appendix displays the estimates of the financial parameters.

Figure 3: Probability of Being Liquidity Constrained.



Notes: Week 24 is the harvest (*i.e.* when the farmers collect their cash revenue). Each vertical line displays the empirical distribution (among the poor farmers) of the Probability of being Liquidity Constrained (PLC) given by: $PLC_i = \mathbb{P}(p_t j_{it} > \mu_{it})$, where i indexes the poor farmers (see appendix B.2 for details). Each week of the year displays a vertical line with: (1) an upper whisker that represents the 95th percentile of the PLC; (2) a black circle marker that represents the mean PLC (the mean PLC among the poor farmers); and (3) a lower whisker that represents the 5th percentile of the PLC.

6 Welfare

In this section we use the estimated demand system (from the first stage) to compare welfare under auctions, quotas, and the highest-valuation (HV) allocation.[24] For the welfare analysis we use specification 2 for the productivity shocks.[25]

6.1 Welfare Measures

In this subsection we describe how we construct welfare measures. Given rainfall and the allocation of water among farmers, the yearly average revenue per tree for farmer i is given by:

$$Revenue_i = \frac{1}{\#\ trees_i}\frac{1}{T}\sum_{t=1}^{T}\left[Revenue_{it}\right] = \frac{1}{\#\ trees_i}\frac{1}{T}\sum_{t=1}^{T}\left[\sum_{w_t=1}^{52} h\left(M_{i,t-1}, w_t\right) - \left(\zeta_j\right)\right]. \quad (10)$$

Note that we do not take into account the expenses in water because we are interested in welfare measures (*i.e.* transfers are not taken into account).

Welfare is defined as follows:

$$Welfare_i = \frac{1}{\#\ trees_i}\frac{1}{T}\sum_{t=1}^{T}\left[Welfare_{it}\right] = \frac{1}{\#\ trees_i}\frac{1}{T}\sum_{t=1}^{T}\left[\sum_{w_t=1}^{52} h\left(M_{i,t-1}, w_t\right) - \left(\zeta_j + \epsilon_{ijt}\right)\right]. \quad (11)$$

The only difference between revenue in equation 10 and welfare in equation 11 is the choice specific unobservable component, ϵ_{ijt}. Since the error term ϵ_{ijt} is choice-specific, the relevant elements are differences in ϵ_{ijt} across choices, and not ϵ_{ijt}. For example, in the

[24] The HV allocation corresponds to the static first-best allocation. However, due to dynamics and the possibility of strategic delaying in the decisions to purchase water it may not coincide with the dynamic first-best allocation, which is a complex problem that is outside the scope of this paper.

[25] We obtained similar welfare results using specification 1 for the choice specific productivity shock. We also obtained similar results using an autoregressive specification for the productivity shock. Results are available upon request.

case in which $J = 1$, the farmer chooses whether to buy 1 unit or not to buy. The farmer balances the difference in utility between buying or not, considering both the observable and unobservable (for the econometrician) components. The probability of a farmer buying water increases with the expectation of the difference in ϵ_{ijt}, *i.e.*, with $\mathbb{E}\left[\epsilon_{i1t} - \epsilon_{i0t}\right]$.

By construction, the unconditional mean of the differences in the error term is zero. Hence, in the quotas system, since the farmers cannot choose when to irrigate, the expectation of the difference in the error term is zero, *i.e.*, $\mathbb{E}\left[\epsilon_{i1t} - \epsilon_{i0t}\right] = 0$. However, in the auction system, farmers choose when to irrigate and the conditional expectation is nonzero. Farmers are more likely to irrigate when their unobserved utility of irrigation is positive, *i.e.*, $\hat{\epsilon}_{i1t} > \hat{\epsilon}_{i0t}$. This implies that under the auction system: $\mathbb{E}\left[\epsilon_{i1t} - \epsilon_{i0t} | j = 1\right] > 0$ and $\mathbb{E}\left[\epsilon_{i0t} - \epsilon_{i1t} | j = 0\right] > 0$. In other words, in the auction system, gains from trade are realized. In the model, gains from trade are translated into the timing of irrigation. Farmers "trade" with each other in order to irrigate at their preferred time. For this reason, welfare is always greater than revenue under the auction system.

We compute the welfare for the following allocation mechanisms: (1) Auctions using complete units, Ac, wherein complete water units are assigned to the farmer who bought them as observed in the data; (2) Quotas with random assignment of complete units, Qc, wherein every time we observe a farmer purchasing a unit of water under the auction system, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among all farmers; (3) Quotas with sequential assignment of complete units, $QcX\%$, wherein every time we observe a farmer purchasing a unit of water under the auction system, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among the X% of farmers who did not receive irrigation the longest;[26] and (5) the

[26] That is, we keep track of when was the last time that each farmer irrigated under the quotas system. Then, to allocate a unit of water on week t, we only consider the subset of farmers whose last irrigation was farthest away from t (this is, the subset of farmers who value the water the most). Then we allocate the unit of water uniformly at random (proportional to their amount of land) among this subset of farmers. The value of X defines how large is this set. For example, if $X = 100\%$, then all farmers are included in the set and the unit of water is allocated uniformly at random (proportional to their amount of land) among *all* farmers.

Formally, the subset is defined as follows. Let $t_i^{Last} < t$ be the last week farmer i was allocated a unit highest-valuation allocation using complete units, HVc, wherein every time we observe a farmer purchasing a unit of water under the auction system, the complete unit of water is assigned to the farmer who values the water the most. In all cases (Ac, Qc, $QcX\%$, and HVc) we compute the welfare measures using the actual allocation of water from the data under the auctions system (*i.e.* the total amount of water allocated in all mechanisms is the same) and the estimates in column 7 from Table 3.[27]

As explained in Subsection 2.2, the quota system in Mula allocates units in sequential rounds of three weeks. So $Qc25\%$ is closest to this system. We now describe how we compute the welfare measures under each mechanism.

Auctions using Complete Units (Ac)

We compute both revenue and welfare.

- **Poor farmers:** We compute revenue using the estimated demand system (*i.e.* $\hat{\Theta} \equiv \left(\hat{\gamma}, \hat{\sigma}_{\varepsilon}, \hat{\zeta}\right)$) and actual purchases made by poor farmers. We use equations 10 (revenue) and 11 (welfare), and the moisture level in the farmers' plots (*i.e.* the moisture resulting from their actual purchase's decisions).

- **Wealthy farmers:** We compute the revenue using the estimated demand system (*i.e.* $\hat{\Theta} \equiv \left(\hat{\gamma}, \hat{\sigma}_{\varepsilon}, \hat{\zeta}\right)$) and the actual purchases made by wealthy farmers. We use equations

of water under the quota system. Let I be the total number of farmers and let $\mathcal{I}$ be the set of all farmers. Let us index the farmers according to the last time that each farmer irrigated, being farmer I the one who irrigated in the week closest to t and being farmer 1 the farmer who irrigated in the week farthest away from t. Then $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} \leq \cdots \leq t_I^{Last}$. (Note that such ranking can always be done and, typically, can be done using several strict inequalities, depending on how many units have been allocated in the past.) Let $X = x/I \times 100$ for $x \in 1, 2, \ldots, I$. So given X, we can compute $x = X/100 \times I$. Then, under $QcX\%$ we allocate the unit of water uniformly at random (proportional to their amount of land) among the subset of farmers $\tilde{\mathcal{I}}_{X\%} \equiv \{i \in \mathcal{I} : i \leq x,\ with\ x = X/100 \times I\}$. For example, if $I = 10$, $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} < t_4^{Last} \leq \cdots \leq t_{10}^{Last}$, and $X = 30\%$, then $x = 30/100 \times 10 = 3$ and $\tilde{\mathcal{I}}_{30\%} = \{1, 2, 3\}$. So, we allocate the unit of water uniformly at random (proportional to their amount of land) among farmers indexed as 1, 2, and 3. These are the three farmers whose last irrigation was farthest away from t. In case of ties, we include all tied farmers in the subset $\tilde{\mathcal{I}}$. In the previous example, if if $t_1^{Last} \leq t_2^{Last} \leq t_3^{Last} = t_4^{Last} = t_5^{Last} < t_6^{Last} \leq \cdots \leq t_{10}^{Last}$, then $\tilde{\mathcal{I}}_{30\%} = \{1, 2, 3, 4, 5\}$.

[27]We obtain similar results simulating the purchase decisions under the auction system and then using the resulting allocation of water to compute the welfare under quotas and HVc. Results are available upon request.

10 (revenue) and 11 (welfare), and moisture level in the farmers' plots (*i.e.* the moisture resulting from their actual purchase's decisions). Note that the revenue for wealthy farmers can be greater than the HVc average revenue. This is because poor farmers are sometimes liquidity constrained, so wealthy farmers buy more water than the amount required by the HVc allocation.

Quotas (Q)

Revenue and welfare coincide under the quota system because farmers do not choose when to irrigate. We only report one measure that we call "welfare." As explained in Section 2, in this paper we focus on the 24 farmers who only grow apricot trees. These farmers bought 633 units of water under the auction system over the sample period. Under the quota system, we allocate the same number of units of water (633 units) in the same week when these units were bought under the auction. We consider two main quota scenarios. In each scenario we allocate units among the farmers as follows:

- **Quotas with random assignment of complete units, Qc:** every time we observe that a farmer bought a unit of water during the auction on a particular date, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among all farmers.

- **Quotas with non random assignment of complete units, $QcX\%$:** every time we observe that a farmer bought a unit of water during the auctions on a particular date, the complete unit of water is assigned uniformly at random (proportional to their amount of land) among the X% of farmers who did not receive irrigation the longest, on the same date.[28, 29]

[28] For example, in $Qc50\%$, complete units of water are allocated among the 50% of farmers who did not receive irrigation the longest; in $Qc25\%$, complete units of water are allocated among the 25% of farmers who did not receive irrigation the longest; and so on.

[29] As indicated in footnote 26, under $QcX\%$ we need to keep track of when was the last time that each farmer irrigated under the quota system. We do not have this information for the initial weeks in the sample. So, under $QcX\%$, we allocate units uniformly at random (proportional to their amount of land) at the beginning of the sample as described in the procedure in footnote 26.

In Qc and $QX\%$ units are allocated uniformly at random (proportional to their amount of land) among the corresponding set of farmers. We simulate the allocation $S = 1,000$ times under Qc and $QX\%$. In Table 6.2 we report the mean welfare measures across simulations.[30]

Highest Valuation using Complete Units (HVc)

We compute the highest-valuation allocation using complete units (HVc) as follows. Every time we observe that a farmer bought a unit of water during the auctions on a particular date, the complete unit of water is assigned to the farmer who values water the most on that date.

6.2 Welfare Results

Table 4 displays welfare results under auctions, quotas, and the HVc allocation. For the welfare analysis in Table 4 we use specification 7 from Table 3, which is our preferred specification because it uses the most credible specification for the productivity shocks (specification 2 from Section 3) and the production function for the apricot trees from equation 6 as obtained from Torrecillas *et al.* (2000).[31] We report the mean welfare per farmer, per tree, and per year. The bottom part of the table shows the mean number of units per farmer (during the whole period under analysis) under each mechanism. The total amount of water is the same across all mechanisms (*i.e.* 633 units). The differences in welfare across columns are a consequence of differences in moisture levels across farmers.

As expected, under the auction system poor farmers have a lower welfare than wealthy

[30] In a previous draft of this paper, we also computed the welfare under "quotas with random assignment of fractional units" (Qf), whereby every time we observed that a farmer bought a unit of water during the auctions on a particular date, all farmers are allocated a fraction of that unit, proportional to their amount of land, on the same date. The welfare results under Qf are similar to the ones under $Qc100\%$.

[31] In our base line case (specification 7 from Table 3) the quotas $Qc25\%$ produce 7.6% ($(1{,}480.47-1{,}375.67)/1{,}375.67$) more welfare per tree than auctions, Ac. Using specifications 5, 6, and 8 from Table 3, quotas $Qc25\%$ produce, respectively, 6.7%, 7.7%, and 5.1% more welfare per tree than auctions, Ac. We obtained similar welfare results to the ones in Table 4 using the other specifications from Table 3, using an specification that allows for different transformation rates for pre-season ($18 \leq week \leq 23$) and on-season ($24 \leq week \leq 32$), and using an autoregressive specification for the productivity shock. Results are available upon request.

Table 4: Welfare Results

	Auctions complete units		Quotas complete units				High Valuation complete units
	Ac Revenue	Ac Welfare	Qc	Qc75%	Qc50%	Qc25%	HVc
Welfare measures: (mean per farmer, per tree, per year)							
- All farmers pre-season (24 farmers)	972.22	978.82	825.80	907.90	978.37	1042.04	1,055.03
- All farmers on-season (24 farmers)	392.05	396.85	321.83	367.73	405.66	438.43	445.28
- Poor farmers whole season (12 farmers)	1,178.04	1,189.44	1,152.79	1,295.77	1,395.70	1,444.91	1,448.40
- Wealthy farmers whole season (12 farmers)	1,550.50	1,561.91	1,142.48	1,255.47	1,372.75	1,516.03	1,552.22
- All farmers whole season (24 farmers)	1,364.27	1,375.67	1,147.64	1,275.62	1,384.02	1,480.47	1,500.31
Amount of water allocated: (mean number of units per farmer)							
- Poor farmers whole season (12 farmers)	19.42	19.42	25.62	27.09	27.44	26.52	26.39
- Wealthy farmers whole season (12 farmers)	33.33	33.33	27.13	25.66	25.31	26.23	26.36
- Total units allocated whole season (24 farmers)	633	633	633	633	633	633	633

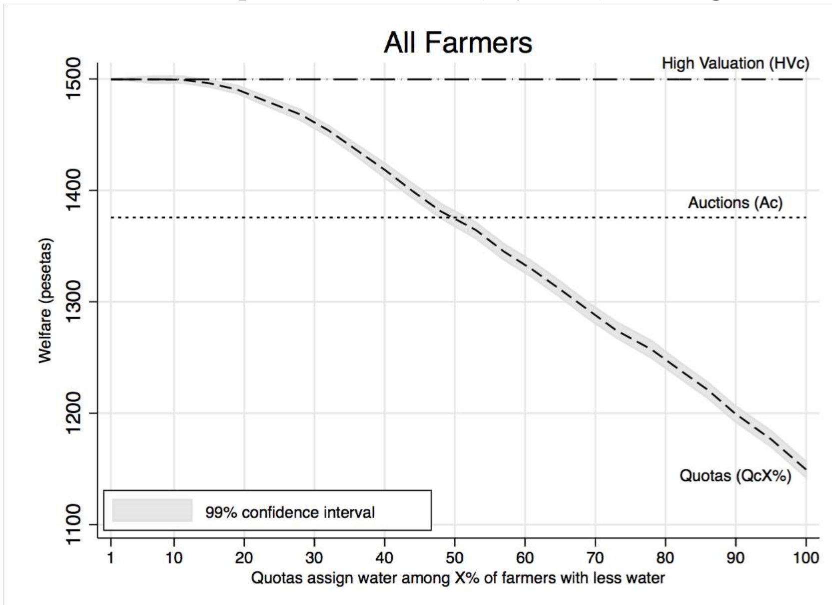
Notes: See Subsection 6.1 for a discussion about the computation of the welfare measures.

farmers. The quota system increases poor farmers' welfare and decreases wealthy farmers' welfare. Table 4 shows that the following ranking holds in terms of efficiency: $HVc > Qc25\% > Qc50\% \cong Ac > Qc$, where a "greater than" inequality indicates greater welfare and where the symbol "$\cong$" indicates that the welfare is not statistically different. That is, randomly allocating the complete units of water, in proportion to amount of land, results in a decrease in efficiency relative to auctions. In $Qc50\%$, complete units of water are allocated among the 50% of farmers who have received less water in the past, in proportion to their amount of land. The welfare under $Qc50\%$ is not statistically different than the welfare under Ac. (Recall that the welfare under Qc is simulated S times.) In $Qc25\%$, complete units of water are allocated among the 25% of farmers who have received less water in the past, in proportion to their amount of land. The welfare under $Qc25\%$ is greater than under Ac. In Mula, the quota allocation mechanism was closer to $Qc25\%$ than to Qc because every farmer was assigned a certain amount of water every three weeks (the duration of a round), proportional to their plot's size.

Auctions, Quotas, and Highest Valuation. Figure 4 shows the welfare comparison among auctions Ac, the HVc allocation, and quotas $QcX\%$ for $X \in [1, 2, \ldots, 100]\%$. (Note that auctions Ac and HVc are constant in X.) The figure shows the mean welfare per farmer, per tree, and per year. (The welfare measures are the same as in Table 4.) The main difference between HVc and auctions is that poor farmers do not buy much water during the critical season under auctions, Ac. Note that $Qc100\%$ is equivalent to quotas with random assignment of complete units, Qc. Allocating randomly the complete units of water, in proportion to amount of land, results in a decrease in efficiency relative to auctions. This is due to the decreasing marginal returns of the apricot's production function. Although all farmers receive the same amount of water per tree, the timing of the allocation is important.[32]

[32]For example, consider the case of two identical farmers: A and B. Suppose there are four units of water to be allocated in four subsequent weeks: 1, 2, 3, and 4. Allocating the first two units during weeks 1 and 2 to farmer A, and the second two units during weeks 3 and 4 to farmer B, results in a lower welfare than allocating the first unit to A, the second unit to B, the third unit to A, and the fourth to B.

Figure 4: Welfare Comparison: Auctions, Quotas, and Highest Valuation



Notes: See Subsection 6.1 for a discussion about the computation of the welfare measures.

On the other hand, as X decreases, the quota system $QcX\%$ allocates units among the farmers who irrigated less in the past. This is similar to the HVc allocation, where water is allocated to the farmer who values water the most. In the limit, as X decreases enough, the welfare under $QcX\%$ is similar to the welfare under HVc.

In practice, varying X is equivalent to varying the duration of the round. Long rounds mean that farmers do not irrigate often, while short rounds mean that farmers incur irrigation costs often.

Yearly Results. Figure 5 shows the welfare results by year (1955 to 1965) and by allocation mechanism (Ac, Qc, $Qc50\%$, and HVc). There is substantial variation across years, due to variation in rainfall. Revenue is lowest for both poor and wealthy farmers during 1962-63, the driest years in our sample (see Figure 3 in appendix A).

The top two panels in Figure 5 display welfare disaggregated by poor and wealthy farmers under Ac, Qc, $Qc50\%$, and HVc. Although the overall performance of Ac is similar to Qc, the distribution is different. As expected, wealthy farmers perform better under Ac than

Figure 5: Welfare by Year.

Notes: See Subsection 6.1 for a discussion about the computation of the welfare measures.

under $Qc50\%$. Poor farmers perform better under $Qc50\%$ than under Ac. Indeed, during drought years (such as 1958, 1963, and 1964) poor farmers perform better under Qc than under Ac. The difference between Ac and HVc is the highest in 1963, the year with the highest drought in the sample. The drought increased the price of water relative to the other years in the sample. The negative impact of this drought on poor farmers under Ac (top panel) was greater than its positive impact on wealthy farmers (middle panel).

7 Discussion

Unobserved Heterogeneity. The differences in production (as a measure of welfare) in Table 4 are due to differences in soil's moisture levels (*i.e.* some farmers irrigate more than others) because our specification assumes that all farmers are equally productive, up to an idiosyncratic productivity shock. An alternative explanation would be that differences in production are due to unobserved differences in productivity. For example, it could be that wealthy farmers used additional productive inputs (*e.g.* fertilizers, hired labor, manure, *etc.*) in greater quantities than did poor farmers. Thus, poor farmers' production would be lower than wealthy farmers' production due to both differences in soil's moisture levels and greater use of these additional productive inputs.

Although we cannot rule out this argument explicitly, it does not affect our counterfactual results from Table 4. We cannot rule it out explicitly because our econometric specification does not allow for persistent differences in productivity among farmers and we have no data about the relative use of these additional productive inputs. However, it does not affect our counterfactual results in the historical context of Mula. Artificial fertilizers were not introduced in Mula until the 1970s. However, farmers did use manure and mules when farming the land. If poor farmers faced liquidity constraints (LC) when buying water, it is reasonable to believe that they also faced LC when buying these other inputs or capital (manure and mules). So if wealthy farmers used additional productive inputs in greater quantities than did poor farmers (under the auction), the transition from auctions to quotas would increase the production of poor farmers more than we predicted in the counterfactual from Table 4. This is because, under quotas, farmers do not have to make large payments for water (maintenance costs are substantially lower than the prices of water under the auction), leaving them extra cash to buy additional productive inputs. In other words, under quotas poor farmers are less likely to be liquidity constrained to buy *other* inputs. So even if poor farmers were less productive than wealthy farmers during the auctions period (due to underuse of inputs/capital), they would be as productive as wealthy farmers under the quotas.[33] Next we further explore this issue by generalizing the model and allowing correlation between wealth and land quality (or productivity).

Correlation Between Wealth and Productivity. Throughout the paper we assume that there are no persistent differences in productivity between wealthy and poor farmers. Although this hypothesis is untestable, we believe it is reasonable in the historical context of Mula. All farmers' plots are located in a small, relatively flat area spanning less than 2 km; thus, weather conditions are the same. To the best of our knowledge, there are no historical sources mentioning (explicitly or implicitly) differences in productivity among farmers, or between wealthy and poor farmers. Table 5, Panel A, shows that although wealthy farmers have larger plots (column 1), when considering all agricultural products there are no differences in revenue per tree (column 5) between poor and wealthy farmers in 1954 (the only year where revenues are observed). Interviews with surviving farmers confirm this. The differences between poor and wealthy farmers (columns 2, 3, and 4) are attributable to the larger plots of wealthy farmers. Note that the year leading to the revenue in 1954 was particularly dry (water prices were substantially higher than other years in the sample). So we would expect large differences in revenue per tree if differences in productivity were

[33] In terms of the model, this can be interpreted as a weaker assumption required for the welfare results to hold. The welfare analysis only requires that poor farmers are as productive as wealthy farmers under quotas (not under auctions), which is a credible assumption in the historical context of Mula as explained above.

large. However, Table 5, Panel B, shows that there are only large differences in revenue per tree for farmers who only grow apricot trees. These differences are accounted by moisture's differences (lower water purchases) of poor farmers relative to wealthy farmers during the critical season in 1954.

Moreover, Table 5, Panel B, shows that among farmers who grow only apricot trees, wealthy farmers obtain greater revenue than poor farmers. However, if a farmer grows another agricultural product in addition to apricot trees (*e.g.* oranges), then there are no substantial differences between wealthy and poor farmers. Moreover, revenue for oranges is not correlated with the wealth of the farmer either. This is because oranges are harvested in winter, unlike apricots, which are harvested in the summer when the prices of water in the auction are high. Prices of water during the orange's harvest season are low, thus LC plays no role. Farmers who grow both apricots and oranges use the cash obtained in winter from the orange's harvest to buy water for apricots in the summer. Similarly, farmers use cash obtained from the apricot's harvest to buy water for oranges in winter. Hence, these multi-crop farmers are not affected by LC. Farmers who only grow apricots do not have access to this "cash smoothing mechanism" and are therefore affected by LC. Results for other agricultural products harvested in the summer such as lemons and peaches are similar to those for apricots. The results in Table 5, Panel B, provide evidence of both LC and low productivity heterogeneity. Column (1) shows that the average revenue per apricot tree for farmers growing only apricots is substantially lower for poor farmers. Column (2) shows that the revenue per orange tree is similar for poor and wealthy farmers. Column (3) shows that the same is true among the farmers who grow apricots and other crops, as well as for lemons and peaches. We interpret these results as evidence that the differences in revenue observed among the farmers who only grow apricots are due to differences in input utilization (*e.g.* water) used by wealthy and poor farmers, and not due to differences in their production function.[34]

[34]When looking at the revenue per tree for wealthy farmers, farmers growing only apricot trees have a greater revenue than farmers growing also other crops. The reason behind this result is that wealthy farmers

Table 5: Farmers characteristics and wealth.

Panel A: Size and Composition of Plots and Wealth, for all agricultural products.

	(1) Area Total (Ha)	(2) Area with trees (Ha)	(3) Fraction with trees	(4) Revenue (*pesetas*)	(5) Revenue/ area (*pesetas*/m^2)
Urban real estate	34,023***	22,069***	-0.0355	23,894***	-0.1797
	(9,747)	(7,031)	(0.0320)	(4,024)	(0.7543)
Number of observations	388	388	388	388	388

Notes: All regressions are OLS specifications. The dependent variable is the variable in each column. "Urban real estate" measures the value of a farmer's urban real estate in pesetas. Standard errors in parentheses. * p<0.10; ** p<0.05; *** p<0.01.

Panel B: Revenue per tree in 1954 for each agricultural products.

		Apricot (only) (1)	Orange (other) (2)	Apricot (other) (3)	Lemon (other) (4)	Peach (other) (5)
Total	Rev. per tree	134.21	125.13	124.70	112.92	51.81
	# trees	73.0	152.0	90.0	102.4	93.1
Low urban real estate	Rev. per tree	105.47	131.65	129.69	120.37	47.09
	# trees	73.6	137.8	71.8	97.0	81.6
High urban real estate	Rev. per tree	162.94	119.48	119.23	105.93	55.58
	# trees	73.4	164.6	109.0	107.4	102.3
# farmers		24	322	239	64	45

Notes: Own elaboration from the 1954 Agricultural census. "CROP (only)" refers to the revenue generated by CROP trees for farmers that only grow CROP trees. "CROP (other)" refers to the revenue generated by CROP trees for farmers who grow CROP and other trees. (CROP represents Apricot, Orange, Lemon, and Peach.) "High urban real estate" ("Low urban real estate") is a dummy variable that equals 1 if the value of urban real estate of the farmer is above (below) the median and 0 otherwise.

The evidence presented above suggests that correlation between wealth and productivity is small. (The actual correlation coefficient between urban real estate and revenue per tree in 1954 is -0.06.) Nonetheless we performed a sensitivity analysis to examine how large the correlation should be to revert the welfare results from Table 4.[35] We explore this by generalizing the model and allowing for correlation between wealth and land quality (or the use of additional inputs). One simple way to do this is to allow the apricot's production function, $h(M_{t-1}, w_t; \gamma)$, to shift with wealth. Let Φ_i be a factor multiplying the apricot's production function of farmer i and be given by:

$$\Phi_i \equiv 1 + \rho_{w,p}\mathrm{NW}_i + (1 - \rho_{w,p})\vartheta_i \qquad \forall t, \tag{12}$$

where $\rho_{w,p} \in [0, 1]$ is the correlation between wealth and productivity, NW_i is the normalized wealth of farmer i such that $\mathbb{E}(\mathrm{NW}_i) = 0$ and $\mathbb{V}(\mathrm{NW}_i) = 1$, and ϑ_i is an *i.i.d.* random shock to farmer i such that $\mathbb{E}(\vartheta_i) = 0$ and $\mathbb{V}(\vartheta_i) = 1$. Note that $\mathbb{E}(\Phi_i) = 1$. Also note that if $\rho_{w,p} = 0$, then we are back to our original model with no correlation between wealth and productivity.

Data about land quality or the use of additional inputs is not available, so it is impossible to pin down the correlation parameter, $\rho_{w,p}$, from the data. To perform the sensitivity analysis we simulate the model for different values of $\rho_{w,p}$ using equation 12 (see appendix B.5 for details).

Figure 6 shows the sensitivity of the welfare results from Table 4 to the correlation between wealth and productivity, $\rho_{w,p}$, for $\rho_{w,p} \in [0, 1]$. The figure displays the welfare difference between quotas minus auctions as function of $\rho_{w,p}$ and as percentage of the welfare under auctions with $\rho_{w,p} = 0$ (the baseline in Table 4). The top panel displays the welfare of quotas $Qc25\%$ minus the welfare of auctions Ac. In our base line case in Table 4 $\rho_{w,p} = 0$ and

growing only apricot trees have a lower average number of trees (72 trees) than farmers growing also other crops (109 trees). This is due to disseconomies of scale. The number of trees for poor farmers growing only apricot trees is 73, thus disseconomies of scale play no role when comparing poor and wealthy farmers.

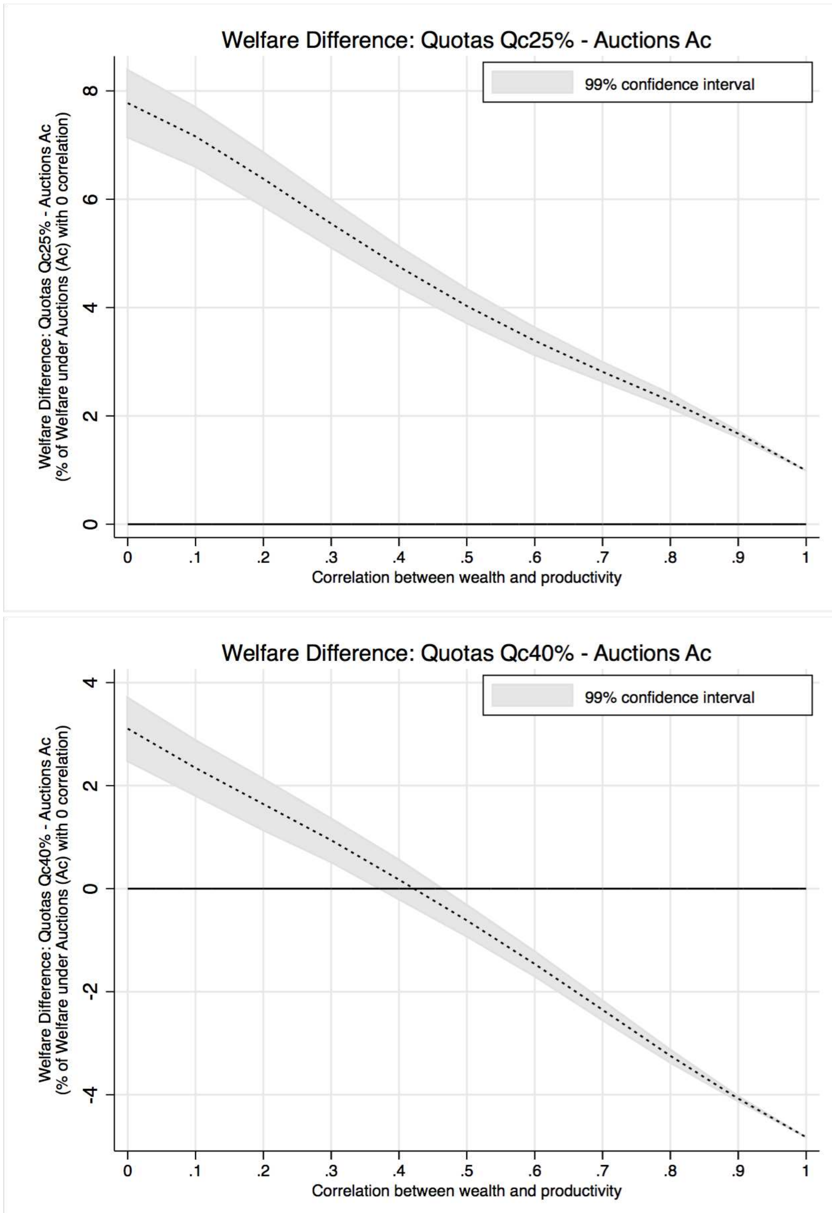
[35] We thank the editor for this suggestion.

the quotas $Qc25\%$ produce 7.6% ($^{(1{,}480.47-1{,}375.67)}/_{1{,}375.67}$) more output per tree than auctions Ac. As expected, as the correlation increases, quotas are relatively less efficient than auctions. (When $\rho_{w,p} \in [-1, 0]$ the welfare difference of quotas minus auctions is larger.) In the extreme case where $\rho_{w,p} = 1$ (*i.e.* wealthy farmers are always more productive than poor farmers with the same level of moisture), the welfare difference between quotas $Qc25\%$ and auctions Ac is minimal because under auctions wealthy farmers buy more water during the critical season than do poor farmers (Figure 2).

The top panel in Figure 6 shows that quotas $Qc25\%$ are more efficient than auctions Ac even when wealth and productivity are perfectly correlated (*i.e.* when $\rho_{w,p} = 1$). This may seem counterintuitive because by moving from quotas $Qc25\%$ to auctions Ac there is a transfer of water from wealthy (more productive) to poor (less productive) farmers according to equation 12. However, note that equation 12 defines a shifter in productivity (*i.e.* wealthy farmers are more productive than poor farmers) for farmers with the same level of moisture. The apricot's production function is concave in moisture, so the lower the moisture level, the greater the productivity, conditional on the correlation between wealth and productivity. Under auctions Ac, wealthy farmers have substantially higher levels of moisture than poor farmers and, thus, wealthy farmers are less productive than poor farmers (due to the concavity of the apricot's production function, even when wealthy farmers are more productive than poor farmers for the same level of moisture). Hence, a redistribution of water from wealthy to poor farmers under quotas $Qc25\%$ results in a net increase in efficiency because the increase in efficiency due to the concavity of the production function is greater than the decrease in efficiency due to the water being used by "less productive" poor farmers (the latter effected captured by equation 12).

The bottom panel in Figure 6 displays the welfare of quotas $Qc40\%$ minus the welfare of auctions Ac. In our base line case in Table 4 $\rho_{w,p} = 0$ and the welfare difference of auctions $Qc40\%$ minus auctions Ac is approximately 3 percent. Now, as $\rho_{w,p}$ increases, quotas $Qc40\%$ are less productive than auctions Ac in contrast to the top panel, where quotas $Qc25\%$ are

Figure 6: Efficiency gains as a function of the correlation between wealth and productivity.



Notes: See Subsection 6.1 for a discussion about the computation of the welfare measures in this figure.

always more efficient than auctions. Note, however, than both panels in Figure 6 show that auctions are relative more efficient than quotas as $\rho_{w,p}$ increases (downward slope). This is due to the shifter in productivity from equation 12. In each panel the mechanisms to allocate water are fixed ($Qc25\%$ and Ac in the top panel, and $Qc40\%$ and Ac in the bottom panel), so there is no increase in efficiency due to the concavity in the production function as $\rho_{w,p}$ varies. The increase in efficiency due to the concavity in the production function can be seen in Figure 4 for a given value of correlation between wealth and productivity, $\rho_{w,p} = 0$.[36]

Strategic Supply. The president of the *Heredamiento de Aguas* decided whether to run the auction or not. There is no evidence that running the auction, or not, was a strategic decision. If there was enough water in the dam, the auction was held. However, the president could stop the auction at any time, andused to do it if the price fell considerably, usually to less than 1 *peseta*. This uncommon situation happened only after an extraordinarily rainy season. The president's decision about when and whether to sell water was profit-maximizing, not necessarily welfare-maximizing.

Strategic Size and Sunk Cost. The results obtained when comparing revenue from quotas and auctions suggest that the choice of the unit size in the auction (*i.e.* three hours of irrigation) was not innocuous. In particular, the fact that in some years poor farmers under the quota system produced higher revenue than wealthy farmers under the auction system suggests that the size of the units sold at the auction might be too large. The size of the units sold at auction had not changed since the middle ages. This could be due to institutional persistence or due to technical reasons. For example, three hours could be the size that maximizes revenue. So it could be the case that three hours maximizes profits, but not welfare.

As shown in Donna and Espín-Sánchez (2015), there is a sunk cost to the first unit of water allocated to a plot because the dry channel absorbs some water. Subsequent units

[36] In principle, one could argue that the shifter in productivity from equation 12 could be large enough such that the slope of the lines in Figure 6 were steeper and, hence, auctions Ac outperformed quotas $Qc25\%$ for large values of $\rho_{w,p}$. We believe this is not the case in the historical context of Mula given the information presented in Table 5, where the correlation coefficient between wealth and revenue per tree in 1954 is $\rho_{w,p} = -0.06$. Also as emphasized above, data about land quality or the use of additional inputs is not available, so it is impossible to pin down the contribution of the shifter in productivity, $\rho_{w,p}$, from the data. Note that if the production function is linear, and wealth and productivity are perfectly correlated, auctions are always more efficient than any mechanism of quotas.

associated with the same channel flow through a wet channel, thus, the loss is negligible. In the auction system, subsequent units are allocated to different farmers, depending on who has won each unit. The optimal size of the unit (*i.e.* the size of the unit that maximizes welfare) would be determined by a trade-off between the sunk cost incurred every time a farmer irrigates, due to the loss of water flowing through a dry channel, and the diminishing return of water. In the quota system, units are allocated to each farmer in geographical order (*i.e.* every unit is allocated to a neighbor farmer down the channel with respect to the previous farmer).

Optimal Mix of Crops. Our analysis only considers the case in which farmers grow apricot trees. Since different agricultural products have different irrigation needs in different seasons, the optimal crop mix involves diversifying among several agricultural products with different irrigation needs. For example, oranges are harvested in winter, and their need for water peaks in December. Apricots are harvested in summer, and their need for water peaks in May-June. Hence, a mix of crops with apricot and orange trees would outperform one with just apricot trees. We observe this optimal mix in the data. Many farmers have orange trees and either apricot, peach, or lemon trees, all three of which are harvested during summer. In this paper we focus on the set of farmers who only grow apricot trees because they have the same production function. This allows us to account for unobserved heterogeneity without modeling it, as discussed above in this section.

Trees. Quotas are desirable during a drought because they allocate a certain amount of water periodically to each farmer. Quotas also function as insurance for farmers, who have less uncertainty when carrying out risky investments, such as trees. A tree takes several years to be fully productive, but will die if it does not get enough water in any given year. On the other hand, vegetables grow more quickly than trees, and can be harvested within a year of planting. Hence, a farmer with a secure supply of water is more likely to plant trees and receive a higher expected profit from them.

Collusion. The presence of a centuries-stable market alongside repeated interaction among farmers raises a concern about bidding collusion in the auction. Historical sources (González Castaño and Llamas Ruiz, 1991) and personal interviews with surviving farmers point in the opposite direction.[37]

Rather than a system in which farmers colluded to pay a price lower than what would have prevailed without collusion, there seemed to be bitterness among farmers competing for water, and between farmers and employees of the cartel. Fights, loud arguments, and complaints were common. In many instances the police intervened during the auction to guarantee its normal development. See Donna and Espin-Sanchez (2015) for a detailed investigation of bidding collusion in this setting.

Liquidity Constraints *vs.* Risk Aversion or Impatience. One concern to identify LC is that some empirical implications of markets where agents face liquidity constraints are similar to those of markets where agents are risk averse. In particular, poor farmers buying water before the critical season (*i.e.* before uncertainty about rain is realized) is consistent with both LC and risk aversion. We now use the response of poor farmers to their purchase timing to investigate this concern.

The main difference in farmers' behavior under LC and risk aversion occurs during the summer, when prices are high. If poor farmers are liquidity constrained, they will not be able to buy water when the price is high, even if the moisture level in their plots is low. On the other hand, if farmers are unconstrained but risk averse, they will have the same demand for water as wealthy farmers during the summer, conditional on soil's moisture levels. Column 4 in Table 2, Panel B, shows that holding the moisture level fixed, poor farmers buy less water than do wealthy farmers. Following the results in this table, along with the opinions presented above, we conclude that poor farmers were liquidity constrained.[38]

[37] A summary of the interview is available upon request.

[38] In this paper we abstract from differences in prices within the week (*i.e.* Monday to Friday, and Day to Night). However, differences in prices within the week can also be used to asses the importance of LC. As shown in Donna and Espín-Sánchez (2015) prices are higher for night-time irrigation and higher earlier in the week (prices on Mondays are higher than on Fridays). Although not reported here, we find that poor

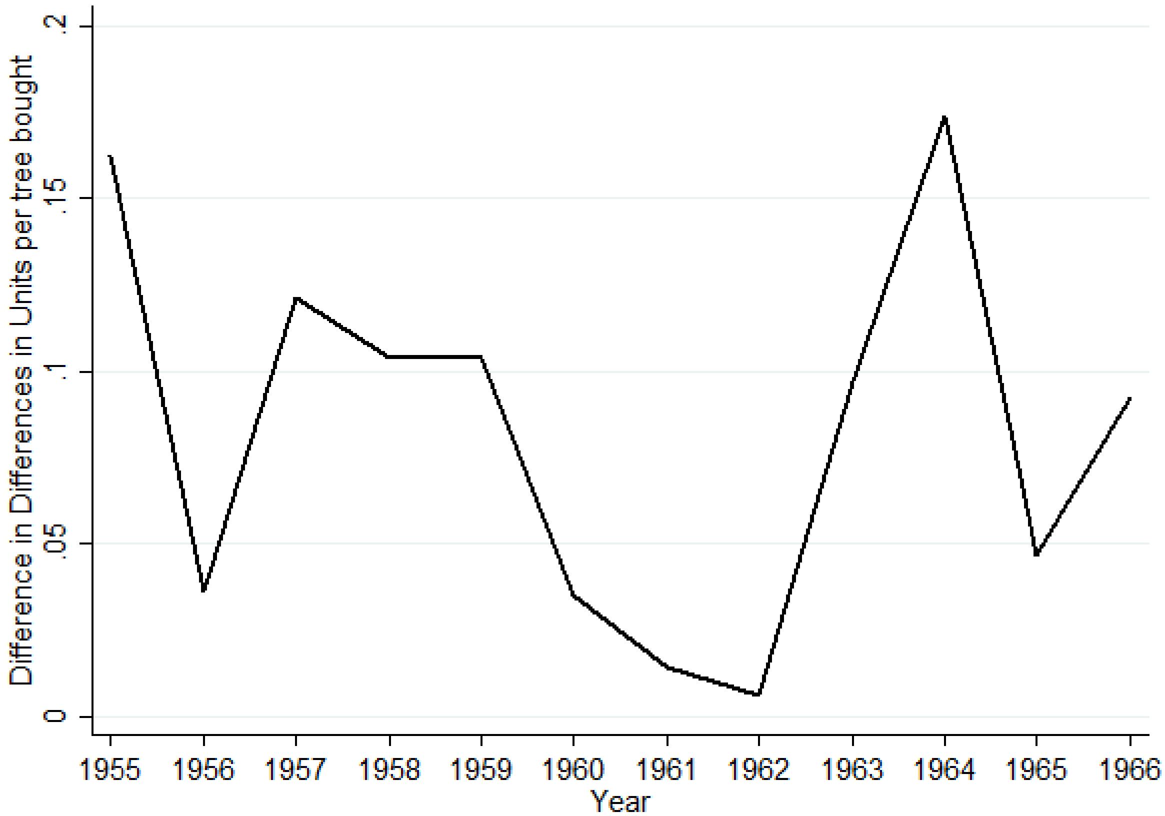
The same argument rules out the possibility that the results are driven by poor farmers being more impatient (lower discount factor) than wealthy farmers. If poor farmers were more impatient, their level of moisture would be always lower than that of wealthy farmers: an extra peseta spent on water has an immediate cost and a future reward. However, poor farmers have higher moisture levels than wealthy farmers before the critical season, lower moisture levels during the critical season, and again high moisture levels right after the critical season (Figure 2).

Attrition. While we have weekly panel data about water purchases, our data only contains one cross-sectional observation of the characteristics of the farmers. The cross-sectional characteristics of the farmers were obtained from a detailed agricultural census carried by the Franco regime in 1955. This agricultural census took place only once, in 1955, to estimate the national capacity to produce agricultural products. One concern about observing cross-sectional characteristics only once is potential attrition in the data. For example, it could be that some of the farmers who only grew apricots in 1955 switched to growing apricots and oranges during the following decade. The incentives to plant other trees, in particular orange trees, would be greater for poor farmers facing liquidity constraints than for wealthy farmers. If poor farmers switched, then we should expect a change in the relative purchases of water during the critical season versus the rest of the year between poor and wealthy farmers (difference in differences).

We investigate this issue in Figure 7, which displays the difference in liters of water bought per tree during the critical *vs.* non-critical season between wealthy and poor farmers over time. If poor farmers were switching, we would expect a downward trend in Figure 7. That is, over time, poor farmers growing only apricots will disappear. This is not what we see in Figure 7. There are large differences between wealthy and poor farmers from year to year. During dry years (1955, 1957, and 1964) price differences in summer are large, so differences in water purchases are also large. During rainy years (1956, 1960, 1961, and

farmers are more likely to buy water during nights and later in the week.

Figure 7: Differences in liters of water bought per tree during the critical vs non-critical season between wealthy and poor farmers (*i.e.* difference in differences).



Notes: For each year, we compute the amount of water per tree bought: *(i) on* and *off* season, and (ii) by wealthy and poor farmers. The figure shows the evolution of the difference in differences for these groups: wealthy *on-season*, wealthy *off-season*, poor *on-season,* and poor *off-season*. The unit of the vertical axis are liters of water per tree.

1962) price differences in summer are small, so differences in water purchases are small. Importantly, there is no trend in the difference in differences data, suggesting that attrition is not a concern in the case of Mula. This is consistent with the notion that switching costs are high, especially for poor farmers.

8 Concluding Remarks

In this paper we empirically investigate the welfare effect of a historical institutional change from auctions to quotas. Both systems allocated water to farmers for agricultural purposes.

A market institution, an auction, was active for more than 700 years in the southern Spanish town of Mula. In 1966, a fixed quota system replaced the auction. Under the quota system, farmers who owned a plot of fertile land were entitled to a fixed amount of water, proportional to the size of their plot, for irrigation.

In the absence of frictions, a water auction is efficient because it allocates water according to the valuation of the bidders. When frictions are present, however, markets may not be efficient. Frictions arose in Mula because farmers had to pay in cash for water won in the auction, but did not always have enough cash during the critical season, when they needed water the most. When farmers are liquidity constrained, the efficiency of auctions relative to quotas is theoretically ambiguous. It is then an empirical question which institution is more efficient.

We show that, as some historians have suggested, some farmers were liquidity constrained in Mula. Poor farmers bought less water than wealthy farmers during the critical season and obtained lower revenue per tree as a result. To compute welfare under auctions and quotas, we estimate the dynamic demand system accounting for three features of the empirical setting: intertemporal substitution effect, liquidity constraints (LC), and weather seasonality. Ignoring the presence of LC biases the estimated (inverse) demand and demand elasticity downwards. We use the estimated demand system to compare welfare under auctions, quotas, and the highest-valuation allocation. We conclude that a necessary condition for quotas to increase efficiency relative to auctions in our setting is that units of water be allocated according to farmers' valuations. In Mula, the institutional change improved efficiency: the quotas generated greater welfare than the market. Hence, the end of the water market in Mula was a "settled problem of irrigation."

The contributions of this paper are twofold. First, from a historical perspective, we provide empirical evidence of a source of inefficiency in water markets. We also provide empirical support for the particular institutional change in Mula proposed in Espín-Sánchez (2015). Second, from an industrial organization perspective, we propose a dynamic demand model that includes storability, seasonality, and LC. We discuss the relationship between storability and LC, and show that ignoring the presence of LC biases the estimated demand downwards.

Our framework could be used to assess the efficiency of water markets in other empirical settings. However, the empirical results in this paper apply only to our empirical setting. One should not conclude that all water markets are inefficient. We have presented an empirical framework incorporating the main components found in other water markets: seasonal demand, storability, and LC.

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